NOAA Technical Memorandum NOS ORCA 73

Evaluation of the Condition of Prince William Sound Shorelines Following the Exxon Valdez Oil Spill and Subsequent Shoreline Treatment:

Volume II 1992 Biological Monitoring Survey

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NOTICE

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CONTENTS

Contents Cont.

ABSTRACT

Biological and chemical data from three years of quantitative monitoring (1990 through 1992) have been analyzed for trends in recovery of biota inhabiting beaches in Prince William Sound from the effects of the *Exxon Valdez* oil spill and subsequent cleanup. Hot-water treatments used to remove crude oil from the beaches of the Sound in 1989 were shown to have severe short-term impacts on intertidal epibenthos. Stratified random sampling was used to assess biota at sites representing several habitats (rocky, boulder/cobble, and mixed gravel/sand) and degrees of disturbance (unoiled, oiled but not hot-water washed, and oiled/hot-water washed).

As of July 1992 concentrations of polycyclic aromatic hydrocarbons (PAHs) in sediments and in mussel and hardshelled clam tissues at oiled sites had declined by one to two orders of magnitude or more since 1990, with the exception of one untreated lower mixed-soft station at Block Island where relatively high concentrations remained. Tissue PAH concentrations from mussels collected at study sites in 1992 were less than those from mussels sampled near Seward and in New Chenega (areas not directly affected by the spill) except at Block Island, where mussel tissue concentrations were similar to those near the villages.

Effects of high-pressure hot-water treatments applied in 1989 remained visible in intertidal assemblages through 1992. Some high-pressure hot-water-treated rocky shores that had been stripped of biota showed little colonization by 1990; significant differences were noted between epibiota on unoiled shores and that on oiled and hot-water treated shores. On other oiled rocky shores that were not high-pressure hot-water washed, the majority of the epibiotic community dominants including rockweed, mussels, barnacles, limpets, drills, and littorines survived.

In May 1991 populations on untreated shores remained depressed compared to those on unoiled shores. By July 1991 most high-pressure hot-water-washed rocky shores showed some recovery, having been colonized by opportunistic species with planktonic larvae; new growth from remnants of the original biota also contributed to recovery. No significant differences remained between unoiled stations and those that had been oiled and not treated; only a few significant differences remained between the biota of unoiled and hot-water-washed shores.

By July 1992 recovery of most rocky shores had progressed considerably, and very few differences remained between the unoiled and the high-pressure hot-water- washed categories. However, individual hot-water-washed sites still showed altered community structure that is attributed to the treatment, and full recovery of intertidal epibiota is still several years away in these areas.

Following three years (1990 through 1992) of quantitative post-spill monitoring, the infaunal assemblages of Prince William Sound sand and gravel (mixed-soft) beaches are beginning to recover from the effects of *Exxon Valdez* oiling and subsequent hot-water washing. The three categories of sampling sites that were defined (unoiled, oiled but not cleaned, oiled and hot-water washed) showed progressively fewer inter-category differences from 1990 through 1992 but still reflected the effects of washing.

Total organism abundance, species richness, species diversity, and abundances of several major taxa (polychaetes, bivalves, gastropods) were significantly lower in hydraulically treated beaches than in unoiled beaches in 1990 and 1991. Oiled but untreated sand and gravel beaches had a richer and more varied infauna than did hydraulically treated beaches. Infaunal variables were negatively correlated with residual PAHs in the sediment total and with sediment coarseness. The fact that total organic carbon (TOC) and percentage of fines were depressed on hydraulically washed beaches suggests that changes in beach morphology and sediment composition resulting from washing were as important as residual hydrocarbons in affecting recovery.

By 1992 relative abundance of major infaunal taxa and the patterns of total abundance, diversity, and species richness remained unchanged among the three shoreline categories (unoiled, oiled but not cleaned, oiled and hot-water washed). Nevertheless, few differences remained among the categories that were both statistically and biologically significant. Total number of infaunal taxa (richness) and species diversity remained significantly lower at hydraulically treated beaches.

Abundance and recruitment of the hardshelled clam (*Protothaca staminea)* was greatly reduced on the hydraulically washed beaches, but were highest on oiled and untreated beaches. Abundance of hardshelled clams remained significantly lower on hydraulically washed beaches in 1992. In clam transplant experiments, growth and survival were negatively correlated with residual sediment PAHs, but bioaccumulation of PAHs was positively correlated with sediment PAHs.

Multivariate analyses confirmed patterns of category differences and trends in recovery of both infauna and epibiota.

EXECUTIVE SUMMARY

INTRODUCTION

It has been estimated that some 40 percent (4.4 million gallons) of the crude oil spilled from the tanker *Exxon Valdez* on March 24, 1989, was deposited on beaches in Prince William Sound. Beach cleanup activities began in May and continued throughout the summer of 1989. More than 500 of the approximately 900 kilometers (km) of oiled shoreline in the Sound were treated in 1989 using various hydraulic wash and bioremediation (fertilization) techniques; additional mechanical cleanup and bioremediation occurred during the summers of 1990 and 1991.

During and after shoreline cleanup activities, concerns were raised regarding the potential effects on intertidal habitats and biota of shoreline treatments, especially those using high-pressure hot-water washes. The overall objectives of this study have been to evaluate recovery of important intertidal and shallow subtidal habitats and resources from the effects of oiling and shoreline treatment and to assess the influence of high-pressure hot-water treatments on the nature and rates of recovery.

STUDY DESIGN AND APPROACH

The study was designed, in part, to document persistence of effects of 1989 hot-water washes, if they remained evident, over the broader area where hot-water treatments had been applied. The effects and status of recovery from the oil spill and subsequent shoreline treatment activities on intertidal community structure were reexamined in 1992 by resampling stations occupied between 1989 and 1991. Primary variables isolated in the intertidal sampling design were habitat type, tidal elevation, degree of oiling, and use of high-pressure hot-water shoreline treatments.

Habitats of interest were productive rocky and mixed sand/gravel (mixed-soft) beaches common in protected embayments. Exposed boulder/cobble habitats that received heavy oiling were sampled to a very limited degree in 1992. Studies sponsored by Exxon in 1989 demonstrated that intertidal assemblage dominants (rockweed, mussels, barnacles, limpets, snails) had survived three to four months in heavily oiled habitats. Significant reductions (50 to 100 percent losses) in all of these dominant species resulted from the high-pressure hot-water washing, however. Because of these identified adverse impacts, ecological effects of this type of treatment were a major focus for the present research effort.

Within each habitat type the authors sampled several beaches that had been unoiled (reference or Category 1 sites), oiled but not treated with warm- or hot-water washes

(Category 2), and oiled and subsequently treated with warm- or hot-water washes (Category 3). Information on initial oiling and shoreline treatments applied at the study sites was derived from detailed review of State of Alaska and Exxon records and through contacts with on-site personnel. While sites were not selected through a strictly random process, the initial set of sites was selected without knowledge of the relative degree of oiling or subsequent treatment.

Quantitative field surveys were conducted in Prince William Sound twice in 1990, twice in 1991, and once in 1992 to document environmental conditions in habitats subjected to a variety of disturbance during 1989. Comparable data from 1989 sampling funded by Exxon have recently been made available but have not been fully incorporated into the analyses.

In 1992 stratified random sampling was used to assess epibiota and infauna at 37 intertidal sites representing several habitats and degrees of disturbance in selected oiled and unoiled locations in the Sound. One to three stations were established at each site to represent intertidal elevations (zones) of biological interest. At each station, multiple quadrats were sampled and, where possible, sediment cores were collected to document the abundance of epibiota and infauna. Samples of selected organisms were collected for age and growth analysis. Samples were also collected for analyses of mollusk tissue and sediment hydrocarbon concentrations. Age and growth studies of selected mollusks (drills, littleneck clams) were continued with additional tagged littleneck clams transplanted between sites for evaluation of factors influencing growth, bioaccumulation of hydrocarbons, and survival.

The design assumed that the habitats selected were similar enough to permit robust comparisons that identify major shifts in species dominance within the biological assemblages. We believe that, despite the limited replication of sites within each station category (habitat, elevation, and treatment category), the results to date accurately suggest the nature of initial impacts and describe the rates of recovery. The longer sequence of monitoring and trend analyses now possible further confirms the validity of the study design in that, for most variables, conditions at Category 2 stations are now similar to those at Category 1 (unoiled) stations. Category 3 stations also appear to be moving in the same direction (i.e., toward recovery), but several key variables are not yet fully recovered.

SIGNIFICANCE OF RESULTS

Sediment Hydrocarbons

Sediment samples from lower mixed-soft stations only were analyzed for hydrocarbons in 1992. Distribution patterns of PAHs in sediments in 1992 were similar to those observed in previous years. Sediment concentrations of PAHs in 1992 were significantly (one to two orders of magnitude) lower at unoiled (Category 1) sites than at oiled (Category 2), or oiled and hot-water-washed (Category 3) sites. On average, Category 2 sites had the highest PAH concentrations, although this was strongly influenced by the Block Island lower mixed-soft station, which had the highest sediment PAH level measured in 1992.

With the exception of Block Island, patterns of hydrocarbon constituents in sediments analyzed in 1992 were consistent with those resulting from weathering of crude oil. In some cases, measurable contributions from diesel oil and/or combustion products were present. Higher concentrations of naphthalenes and fluorenes in sediments at the lower Block Island station reflect less exposure to mechanisms of weathering.

Several compounds occurred at sufficiently high concentrations in sediments at Block Island to raise concerns about chronic (sublethal) effects of exposure. Biological processes that could be influenced by chronic exposures to low levels of PAHs include survival, reproduction, development, and growth. In a transplanting experiment carried out in 1991, there was a clear correlation between higher sediment hydrocarbon concentrations and reduced survival and increased uptake of PAHs in littleneck clams. In 1992 the growth of clams from this transplant experiment was also negatively correlated with sediment hydrocarbon concentration.

Tissue Hydrocarbons

The 1990 studies provided strong evidence of bioaccumulation at several levels in the food web, but found no evidence of biomagnification. Therefore, subsequent PAH analyses focused on determining whether high concentrations of PAHs in mollusk tissues at some sites were due to continued exposure to hydrocarbons or whether they resulted from a one-time exposure. Studies in 1990 and 1992 provided data to evaluate spatial, temporal, and treatment-related patterns in tissue hydrocarbons.

In experiments conducted in 1991, PAH concentrations in tissues of mussels and littleneck clams transplanted from reference sites to areas of high residual sediment contamination increased over the summer by an order of magnitude or more to levels as high as, or higher than, those in resident (local) animals.

It appears that levels of mussel tissue PAHs at study sites have declined steadily with time. For example, levels of contamination observed in resident mussel tissues at Smith Island in July and September 1991 were more than an order of magnitude lower than those observed at that site in July 1990. By 1992 contaminant levels in mussels at most previously oiled sites had dropped by an order of magnitude from levels in 1990.

Levels of tissue PAHs in mussels (transplants and local animals) at Smith Island, considered one of the more highly contaminated sites remaining in the Sound because of the heavy residual deposits of subsurface oil, were similar in 1991 to the levels of PAHs in mussels from the Seward area. (The Seward sample was collected in late April 1991, a period of relative inactivity for watercraft, from a shoreline in an area unaffected by the spill and at least 0.8 km from town.)

At many sites in the Sound, the most likely sources of long-term contamination of mussel tissue are the reservoirs of subsurface oil. Large reductions in PAHs in mussel tissues from Smith Island and elsewhere between 1990 and 1992, however, suggest that either leaching rates from such subsurface deposits of oil have declined dramatically since July 1990, or that the bioavailability of residual oil has decreased. This observation is important when considering the advisability of continued shoreline treatment activities, particularly in view of the fact that, in 1991 and 1992, tissue contamination at Smith Island and other contaminated sites in this program (e.g., Block Island) were no higher than those observed in mussels near Seward and in New Chenega Harbor.

In 1992 another experiment was conducted to further explore the bioavailability of hydrocarbons at Smith Island. Mussels from an uncontaminated site and semipermeable membrane devices (oleophilic "lipid bags") were placed on the island and recovered after two weeks and after two months. After two weeks mussels and semipermeable membrane devices had accumulated comparable levels of PAHs. After two months, the mussels continued to accumulate significant additional PAHs while the semipermeable membrane devices showed little additional uptake.

Epibiota on Rocky Habitats

In 1990 and 1991 sampling, a high degree of seasonal and intersite variability was seen among biota at sites subjected to varying degrees of treatment. Peak abundances of most important taxa occurred in mid-summer; lower abundances occurred in May and September. Many of the important longer-lived dominants remained in abundance at some oiled sites in 1990, but at other areas—apparently those that had been cleaned more rigorously—these species did not survive. In July 1991 colonization of these areas was evident on most shorelines, particularly on rocky substrata. By 1992 most assemblage dominants, even on hot-water-washed beaches, had recovered to levels approximating those on unoiled and untreated beaches. As a consequence, a variability between site categories was reduced.

Measurements of abundance of many key taxa (rockweed, limpets, drills, littorines) over the period of initial impact and subsequent recovery indicated that oiled but untreated (Category 2) stations, which reflected apparent declines in abundance in 1989 and 1990, were well on their way to recovery by mid-1991. That is, there were few significant differences in abundance between Category 1 and 2 stations. While populations at hot-water-washed (Category 3) stations exhibited major recruitment of many taxa between May and July 1991, these stations did not reach the same level of recovery as Category 2 stations until July 1992. By this time abundances of most dominant taxa did not differ significantly among site categories, although treatment-related effects were still evident at some individual stations. The fact that some species (*Littorina scutulata, Semibalanus balanoides*) were much more abundant at hot-water-washed sites in 1992 suggests that reestablishment of biological controls was not complete.

One rocky site in Northwest Bay that was stripped bare by treatments in 1989 showed little colonization at middle and upper stations through September 1991. Films of blue-green algae and possibly other algae that developed early in 1990 and 1991 were grazed or eroded away, and mostly bare rock was left. Even early successional colonization by sporelings of rockweed (*Fucus gardneri*) or the barnacle *Semibalanus balanoides* that were seen elsewhere over broad areas, occurred only sporadically and in isolated patches. By 1992 significant recovery had occurred—portions of the middle station at this site had a dense cover of rockweed and a fairly diverse associated biota. The remaining portions of the middle station and all of the upper station, where the substratum is smooth bedrock, had little recolonization by any species. At the lower station, algal recolonization was dominated by rockweed, in contrast to the red algae dominated assemblage that existed prior to treatment. Clearly, the epibiota at this site will take several more years to recover to conditions resembling those before the spill.

In summary, oiled rocky areas not subjected to high-pressure hot-water washing were generally indistinguishable from unoiled sites by mid-summer 1991. Some high-pressure hot-water-washed sites remained in early stages of recovery in 1991 and were not fully recovered in 1992. Qualitative examinations of other shorelines around the northern portions of the Knight Island group continued to show incomplete recovery in areas where hot-water treatments were used in 1989.

Infauna on Mixed-Soft Beaches

Protected sand and gravel beaches were severely affected in 1989 by hydraulic treatments that altered beach morphology: coarse sands and finer gravels were flushed from upper intertidal elevations and often buried the lower beach in several centimeters of sediment. In this process many infaunal organisms, along with a high percentage of the silts and organic materials in the sediments, were dislodged and transported from the site. Hydraulic treatments left the lower beaches in many areas covered with coarse sediments with a low content of finer material.

Since 1990 macroinfauna have appeared only moderately affected by the spill on Category 2 (oiled but untreated) beaches. Significant differences between Category 1 (unoiled) and 2 stations were few in 1990 and 1991; none were found in 1992. The infauna on Category 3 (oiled and hot-water-washed) beaches, however, remained altered in comparison with both other classes of beaches. Number of species, number of organisms, and species diversity varied significantly among station categories in 1990 and 1991; lowest values were at the hot-water-treated beaches. Most major taxa (gastropods, bivalves, polychaetes, some crustaceans) had significantly lower abundances on Category 3 beaches than on Category 1 and/or 2 beaches in one or more years. The progressive decline in 1991 and 1992 in the number of significant differences between categories (in analysis of variance and multiple comparison t-tests) indicates that recovery is underway. In 1992 only infaunal species richness was significantly lower on the hydraulically washed beaches than on the other two category beaches.

In 1991 and 1992 several dominant taxa were most abundant at the lower intertidal station at the heavily oiled Category 2 site at Block Island. This area continued to show high sediment oiling yet had higher densities of the deposit-feeding bivalve *Macoma* spp., harpacticoid copepods, nematodes, and oligochaetes than any site group in 1991. This suggests that these taxa may be inherently more tolerant of exposure to partially weathered residual hydrocarbons and/or may be capable of exploiting hydrocarbon-degrading bacteria in these oily sediments. In 1992 relative abundance of these groups had declined somewhat at Block Island.

The Block Island lower station also had a high density and the highest recruitment of young-of-the-year littleneck clams in sediment core samples in both 1991 and 1992, despite evidence that residual hydrocarbon concentrations were sufficient to cause reduced survival and growth of clams experimentally transplanted to this station. In all three years the Category 3 sites had the lowest overall density and lowest recruitment rates of hardshelled clams including littlenecks and butter clams.

Analysis of three years of infauna data supports the conclusion that the effects of shoreline treatments relate as much to physical disturbance (burial, displacement, reductions in fines, and organic content) as to oiling or (probably) thermal effects of hot water. Infaunal assemblage variables (total organism density, diversity, and richness) were negatively correlated with percentage of sands and the residual hydrocarbon levels in the sediments. Total organism density was positively correlated with the percentage of fines.

The three years of data indicate that full recovery of infauna on hydraulically washed beaches will take many years. We believe the primary factors prolonging the recovery period on Category 3 beaches are the continued instability of the beach profile, reductions in finer sediments and organic carbon, and alteration of the normal population (age) structure in longer-lived organisms such as the hardshelled clams. Residual sediment oiling may also alter and delay the full recovery at a few Category 2 and 3 stations. The 1991 tagging and transplanting experiment to examine the effects of residual sediment oiling on littleneck clams showed a significant positive correlation of sediment PAHs with clam mortality and bioaccumulation of PAHs in soft tissues, and a significant negative correlation of clam growth with sediment PAHs. We conclude that in 1991, some level of toxicity to this important infaunal species was associated with residual *Exxon Valdez* oil in the sediments. The degree of this toxicity will be further defined through field experiments to be recovered in 1993.

CONCLUSIONS

The existing body of data indicates that high-pressure hot-water treatments:

- ❒ displaced some stranded oil, along with coarse sediments, from upper to lower intertidal elevations

- ❒ removed fines and organic matter from beaches by suspension in the water column

- ❒ reduced abundances of dominant epiflora, epifauna, and infauna including important hardshelled clams to levels significantly below those at untreated beaches.

These conditions appear to have delayed or depressed recruitment of mollusks and other infauna, thereby further impeding recovery. These conclusions are consistent with observations reported in 1989 studies before and after warm- and hot-water treatments at four experimental sites.

Continued bioavailability of hydrocarbons is shown by the rapid bioaccumulation of PAHs in transplanted mollusks in both 1991 and 1992. However, PAH levels in mussels, a key indicator species, declined an order of magnitude from 1990 to 1991 at one of the most heavily oiled sites in the Sound and in 1991 were similar to levels in mussels from near Seward in an area not affected by the spill.

By mid-summer 1991 convergence of many variables measured was apparent and relatively few differences remained between Category 1 and 2 stations. Some recovery was also evident in most variables at Category 3 stations. The lag in recovery at high-pressure hot-water washed sites relative to that at untreated Category 2 stations leads one to question whether the treatments applied achieved the desired objective of oil spill response stated by Lindstedt-Siva (1991) (i.e., to minimize the net ecological impacts).

We suggest that two areas of increased knowledge would be helpful for exploring this question in greater detail:

- ❒ First, a better understanding must be gained of the relative rates of oil degradation and weathering with and without high-pressure hot-water washes and with and without less obtrusive treatments.

- ❒ Second, we must be able to balance the predictable losses of intertidal productivity and habitat that result from treatment against the potential ecological risk to other resources that may be posed by any reduced rate of beach oil removal that results from cleanup decisions.

The first field of information would be addressed most easily and productively outside of a spill response situation, i.e., in the setting of a controlled field experiment. The second consideration represents a spill response tradeoff typical of those that must be considered within the context of a specific habitat and situation. It is hoped that some of the lessons learned from this spill and program will facilitate a more effective response in future incidents, resulting in the minimization of longer-term environmental impacts.

CHAPTER 1

INTRODUCTION

GENERAL

This document is the third annual progress report on studies designed to investigate the ecological implications of shoreline treatments on intertidal and subtidal marine life of Prince William Sound, Alaska, following the March 1989 spill from the T/V *Exxon Valdez.* This program addresses two areas of great uncertainty and concern about the effect of oil on shorelines:

- The length of time required for oil-damaged ecosystems to recover.
- The effects of shoreline treatment methods on marine life and the extent to which treatment affects recovery.

It is important that information regarding shoreline recovery from the *Exxon Valdez* spill and the various treatments applied be made available to decision makers before the next such incident occurs. This need to disseminate information is the general rationale for the present study, initiated by National Oceanic and Atmospheric Administration (NOAA) under Contract No. 50ABNC-2-00050. Funding in 1992 was provided by NOAA, the U.S. Environmental Protection Agency (EPA), the Minerals Management Service (MMS), and the American Petroleum Institute (API).

Several studies conducted shortly after the spill demonstrated the effects of treatment on shoreline marine life. Two Exxon-sponsored studies of the short-term effects of different beach cleaning methods employed in 1989 (the July 1989 Omni-Barge test [Maki and Houghton, 1989; Houghton et al., 1990a] and the Corexit 9580 test [Lees and Houghton, 1990; Lees et al., 1993]) provide data that permit inference of the short-term effects of oiling and describe the short-term impact of hydraulic beach treatments. Both of these high-pressure hot-water washes clearly had significant, similar impacts on intertidal assemblages that had survived extended exposure to heavy oiling.

The 1990 NOAA biological studies in Prince William Sound (Houghton et al., 1991a, b) describe conditions on rocky, boulder/cobble, and mixed-soft beaches and in adjacent eelgrass beds in portions of the Sound that were oiled or oiled and high-pressure hot-water washed in 1989. Biological conditions on these beaches were compared to those on unoiled beaches of similar habitats. The conclusions were that: the effects of high-pressure hot-water washing remained evident in the biological assemblages 16 to 18 months after the spill, and oiled beaches not treated in this manner were well on their way to recovery.

Results of the 1991 NOAA biological studies in Prince William Sound (Houghton et al., 1993) suggested that: effects of high-pressure hot-water washing were still evident 28 to 29 months after the spill, and infaunal and epibiota communities that were not high-pressure hot-water washed were, in some respects, beginning to resemble communities that were not oiled. Additional conclusions indicated that oiling and subsequent treatment may have altered the spawning cycle of mussels and the reproductive strategy of eelgrass. Continued bioavailability of hydrocarbons was shown in the bioaccumulation of PAHs in transplanted mollusks. PAH levels in mussels had declined by an order of magnitude from those seen in 1990, however.

In companion studies to this one, Michel and Hayes (1990, 1991, and 1993) and Michel et al. (1991) documented the changes in beach profiles and hydrocarbon content at many of the sites sampled biologically in this program. These reports describe the physical setting and important geomorphological processes that play critical roles in defining the biological environment of Prince William Sound.

SAMPLING OBJECTIVE AND APPROACH

Objectives

The objectives of this study are to:

- ❐ Assess and compare the effects of oiling and shoreline treatment activities (specifically, high-pressure hot-water washing) in important littoral (intertidal and shallow subtidal) habitats in the fourth year following the spill.
- ❐ Evaluate rates of recovery over several years in areas receiving differing levels of oiling and treatment.

For purposes of this study, "recovery" is defined as the return of the ecosystem to a state within the limits of natural variability (Ganning et al., 1984). Detailed information was obtained on the dynamics and ecological forces driving recovery at a relatively small number of carefully selected sites. Data reported herein were gathered in late June and early July 1992, 39 months after the initial spill. It is anticipated that similar studies in the future will provide longer-term documentation of the recovery process.

Approach

As in previous years, the approach in 1992 involved examination of a broad spectrum of variables representative of the status of and trends in a variety of intertidal assemblages and species. The intent was to produce a body of data covering potential responses of a wide range of biological indicators to hydrocarbon contamination and to various disturbances caused by shoreline treatment. The data were used to compare the effects of hydrocarbon contamination and shoreline treatment, and to compare rates and patterns of recovery in treated and untreated areas. The components examined in 1992 are listed below:

- Analyses of PAHs in surficial sediments.
- Analyses of PAHs in *Protothaca staminea* and *Mytilus* cf. *trossulus*.
- Quantitative studies of epibiota (those species living on the substratum surface): abundance and relative cover.
- Quantitative studies of densities of macro-infauna.
- Population studies of the mollusks *Nucella lamellosa* and *Protothaca staminea*: size structure, length/weight relationships, and growth and mortality rates. These parameters include comparative growth of marked organisms transplanted to areas of differing oiling and treatment history.

Intertidal sampling was conducted from June 26 to July 11, 1992, with two vessels and crews. About 150 person-days were expended in collecting some 174 samples of all types.

Hypotheses Tested

Three treatment categories were defined: Category 1 (unoiled), Category 2 (oiled but untreated or moderately treated), and Category 3 (treated with high-pressure hot-water wash). Within each of these treatment categories, multiple sites were sampled to provide replication for statistical testing. Based upon the stated objective, several null hypotheses were formulated to test for and evaluate the effects of oiling and shoreline treatment on the intertidal and selected shallow subtidal assemblages in selected habitats. These null hypotheses are:

1a. Relative cover of dominant algal taxa does not differ among site categories.

1b. Abundance (density or percent cover) of dominant epifaunal species does not differ among site categories.

2a. Total abundance, number of taxa, and diversity of infaunal taxa in mixed-soft substrata do not differ among site categories.

2b. Density of selected invertebrate species in mixed-soft substrata does not differ among site categories.

3. Tissue hydrocarbon concentrations in *Protothaca staminea* do not differ among site categories.

4. Sediment hydrocarbon concentrations do not differ among site categories.

5. Size structure, growth, and mortality rates do not differ among site categories for selected mollusk populations (hardshelled clams and drills).

6. There is no difference in the nature of (trends in) recovery between site Categories 2 and 3.

SAMPLING DESIGN

A stratified random sampling design was used to assess important intertidal assemblage and population (individual taxa) characteristics. Sampling was structured following Zeh et al., (1981) to obtain statistically reliable estimates of density or cover of macrobiota inhabiting the surface (epibiota) and, where possible, the subsurface (infauna) within important life zones and within typical habitats.

The intertidal sampling effort was initially stratified according to three habitat types important in Prince William Sound:

- Sheltered rocky habitats—Intertidal substratum composed primarily of bedrock or very large boulders (50 centimeters (cm) or larger).
- Boulder/cobble habitats—Exposed beaches with nearly 100 percent cover by rounded cobbles and boulders ranging from about 10 to 50 cm. Some larger materials and/or bedrock outcroppings were occasionally present.
- Mixed-soft habitats—Typically a mixture of silt, granules, and pebbles with varying amounts of cobbles (5 to 25 cm) or boulders (25 to 50 cm).

Sheltered (low energy) rocky and mixed-soft sites were included for two reasons: their biological productivity is high, and their low-energy regime reduces the rate of natural weathering of oil (Jahns et al., 1991; Michel et al., 1991). Exposed boulder/cobble sites were sampled because they represented some of the most heavily oiled beaches in the Sound. Oil often penetrated deeply into the open spaces between the coarse materials of these beaches.

To represent important life zones (i.e., to further stratify the sampling), three elevations or stations, were typically sampled at each site:

- Near the upper limit of attached macrobiota.
- In the upper portion of the broad rockweed-dominated zone.
- Along the lower edge of this rockweed zone.

Thus, in the terminology of this study, a "location," such as Snug Harbor, can have both rocky and mixed-soft "sites," and each site can have up to three "stations" to represent different intertidal zones (Figure 1-1). At each station sampling was conducted at points along a transect line laid parallel to the waterline along the beach contour.

We initially sampled most sites in this study in 1989 using comparable methods. These sites were not initially selected through a systematic randomization process. The goal was to select comparable sites within representative geomorphological habitat types and to include oiled and unoiled sites within each habitat type. The sites selected were accessible by boat and/or helicopter. After site selection, some of the oiled sites were treated; others were established as untreated "set asides." Recent release of 1989 data for these sites, collected under contract to Exxon, extends the biological record to early post-spill and, in most cases, to pretreatment conditions. Such information greatly increases the confidence of statements about the prespill similarity of stations within each site category; to date, however, only partial incorporation of 1989 data into the analyses has been accomplished.

Several sites without 1989 biological data were sampled in 1990 because they represented important substrate types, and because of the record of hydrocarbon trends available through the NOAA geomorphological monitoring program (Michel and Hayes, 1991; Michel et al., 1991). Additional sites and stations were added in 1991 and 1992 to increase the number of stations within a given habitat/treatment category/elevation. New rocky stations were established in 1992 at Mussel Beach North (Category 3) in the upper, middle, and lower intertidal and at North Elrington Island at two adjacent coves in upper, middle, and lower intertidal (Category 3). A new boulder/cobble site was sampled at the middle elevation station only at Point Helen south of the previously established site (Category 3). At mixed-soft sites, a new low station was added at Crab Bay (Category 1), and a new low station was sampled at North Elrington Island West. A total of 72 stations (elevations) at 31 study sites from 18 locations was sampled in 1992. Sites and elevations (stations) sampled, their habitat types, degrees of oiling, and known treatment histories are listed on Table 1-1.

Study sites were monitored from 1990 through 1992 with two broad (and not entirely compatible) objectives in mind to:

- Provide one-, two-, and three-year post-spill "snapshots" of conditions in key habitats subjected to oiling vis à vis those that were unoiled and those that were oiled and high-pressure hot-water washed.

- Establish differences between sites and site categories that may be monitored for convergence as recovery progresses. All site-to-site comparisons and all comparisons for site category effects were restricted to data from within a single tidal range (i.e., middle elevation stations were compared only with other middle stations).

An optimum design to allow generalizations at any one time regarding differences among site categories (i.e., to define effects of treatment versus effects of oiling) would maximize the number of sites sampled in each category. Inclusion of a large number of sites increases the power of statistical tests using means at a given elevation (e.g., all middle stations) as replicates within each site category. Optimum design for tracking long-term recovery at individual stations (convergence with an unaffected station from the same elevations in a similar habitat) would be met through comparisons based on multiple random subsamples at each of the stations.

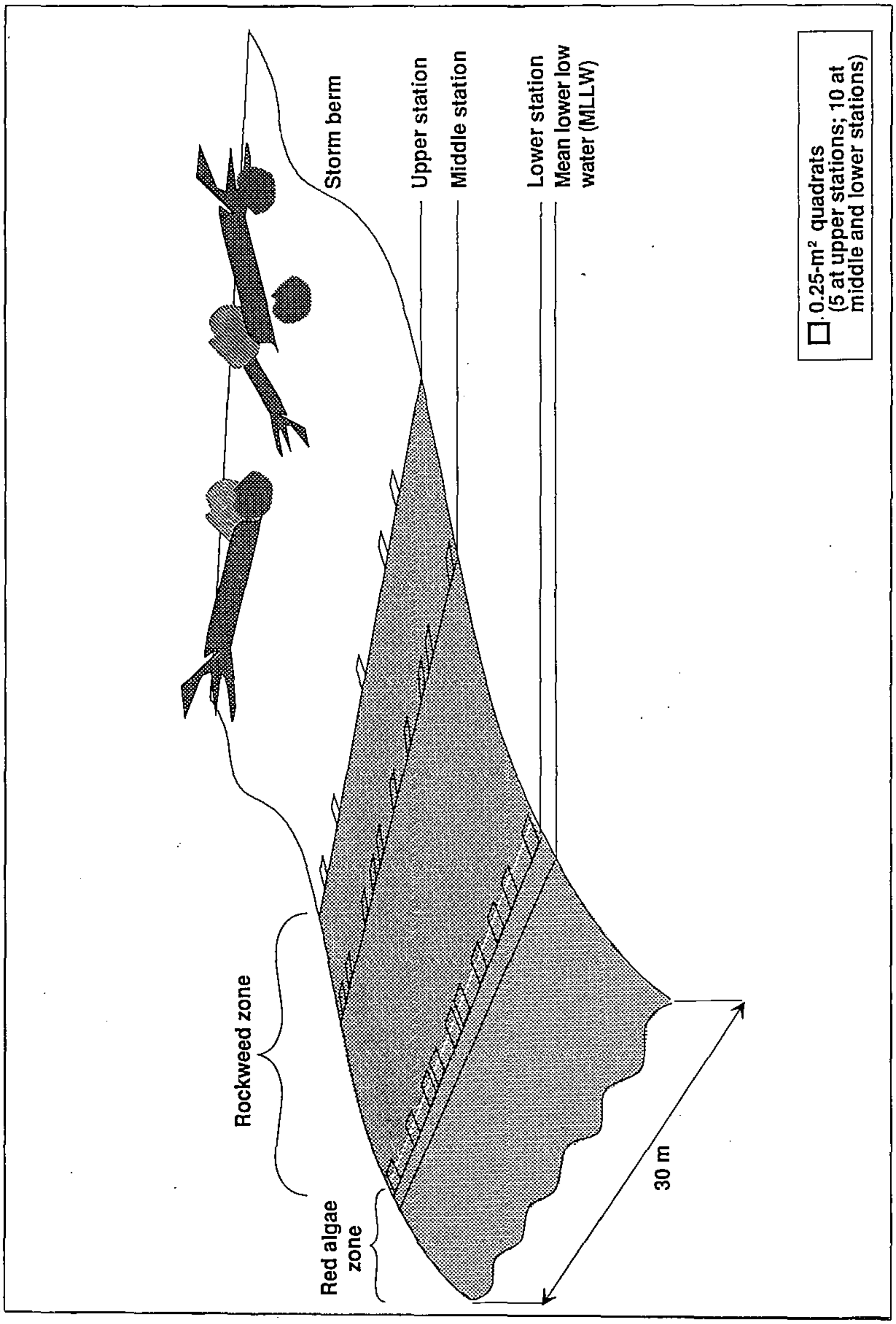

Figure 1-1. Typical site layout.

Table 1-1 Intertidal stations sampled in 1992 by habitat and oiling/treatment category.

	Habitat (degree of oiling)							
	Rocky			Boulder/Cobble		Mixed-Soft		
Elevation	Category 1 [1]	Category 2 [1]	Category 3 [1]	Category 1 [1]	Category 3 [1]	Category 1 [1]	Category 2 [1]	Category 3 [1]
Upper	Bass Harbor	Herring Bay (Hv	Mussel Bch. S (Hvy)	Bass Harbor	Pt. Helen N3 (Hvy)	Crab Bay	Herring Bay (Hvy)	Shelter Bay (Hvy)
	Eshamy Bay	Outside Bay (Lt)	NW Bay Is. (Hvy)			Outside Bay Site 1	Snug (Hvy)	Sleepy Bay (Hvy)
	Hogg Bay	Snug (Hvy)	Block Is. (Hvy)			Sheep Bay		
			Elrington East (Hvy)					
			Mussel Bch. N (Hvy)					
			Elrington Islet - N (Hvy)					
			Elrington Islet - W (Hvy)					
			Elrington Islet - E (Hvy)					
Middle	Crab Bay	Herring Bay (Hv	Block Is. (Hvy)		NE Latouche (Mod)	Crab Bay	Mussel Bch. S (Hvy)*	NW Bay W Arm (Hvy)
	Eshamy Bay	Outside Bay (Lt)	NW Bay Is. (Hvy)		Pt. Helen S (Mod)	Outside Bay Site 1	Snug (Mod)	Shelter Bay (Hvy)
	Hogg Bay	Snug (Hvy)	NW Bay W. Arm (Mod)		Omni site (Hvy)	Sheep Bay		Sleepy Bay (Mod)
			Elrington East (Hvy)		Pt. Helen N3 (Hvy)			Block Is. (Hvy)
			Elrington West (Hvy)					
			Mussel Bch. N (Hvy)					
		NW Bay W. Arm (Mod)**						
Lower	Crab Bay	Snug (Lt)	NW Bay Is. (Hvy)		NE Latouche (Lt)	Outside Bay Site 1	Block Is. (Hvy)*	NW Bay W Arm (Mod)
	Hogg Bay	Outside Bay (Lt)	Elrington East (Mod)		Pt. Helen N3 (Lt)	Sheep Bay	Mussel Bch. S (Lt)*	Shelter Bay (Mod)
	Eshamy Bay		Elrington West (Mod)			Crab Bay	Herring Bay (Lt)	Sleepy Bay (Mod)
			Mussel Bch. N (Mod)			Bainbridge Bight***	Snug (Lt)	Elrington West (Mod)
							Ingot Island (Mod)	

1 Category 1 = Unoiled; Category 2 = Oiled, Untreated; Category 3 = Oiled, Treated.
Note: Stations categorized as oiled and treated are known to have been treated with some form of hydraulic flushing in 1989.

* Nearby upper elevations had been disturbed by treatment; however, there was no evidence of effects on sediments or biota at this elevation. Exception: significant local physical disturbance was evident at Mussel Beach middle, where a vessel reportedly grounded in 1989. This site was also reported to have been washed with cool water.
** There is uncertainty regarding treatment history at this site; thus it was not included in any category analyses.
***Only infaunal cores sampled; no epibiota data collected except photographs.

Analysis of, two high-pressure hot-water test washings in 1989 (Lees et al. 1993) and other research (e.g., Broman et al., 1983) led to a decision to isolate this form of treatment as a variable. No attempt was made to evaluate other forms of treatment or to distinguish among degrees of high-pressure hot-water wash applications. The study plans established for 1990, 1991, and 1992 were designed, in part, to document the persistence of the effects, if they remained evident, of 1989 high-pressure hot-water washes in areas where such treatments had been used. The intermediate-term (37- to 38-month) effects of the oil spill and subsequent shoreline treatment activities on intertidal community structure were examined by resampling stations occupied in previous years. Primary variables isolated in the sampling design remained habitat type, tidal elevation, degree of oiling, and use of high-pressure hot-water shoreline treatments.

Usually only one site could be worked on each tide by each of the two scientific crews. A relatively large number of subsamples was collected at each station at each site visited, and study design tends to favor the objective of long-term trend analysis at individual stations and between station pairs. In addressing this objective, the sampling design can be considered analogous to the "BACI" (Before, After, Control, Impact) approach of Stewart-Oaten et al. (1986), except that, with no prespill data, differences between site categories are expected to diminish over time to a minimal "no-effect" condition that will approximate the prespill condition.

Review of the field design for this study reveals that a preponderance of Category 3 sites was heavily oiled; only about half of the Category 2 sites were similarly oiled. As noted, this difference in degree of oiling between the site categories was an artifact of the shoreline treatment decision-making process (Ciancaglini, 1991) that resulted in relatively few "set asides" of small areas of shoreline to allow monitoring of natural recovery processes without treatment. Four of the heavily oiled sites for which detailed biological data had been gathered early in 1989 (rocky and mixed-soft sites in Herring Bay and Snug Harbor) were included among the ten set-aside sites not treated with high-pressure hot-water washes.

Conditions at these Category 2 sites compared to conditions at Category 3 sites of similar habitat and oiling in Northwest Bay (rocky and soft), Shelter Bay (mixed-soft), Mussel Beach (rocky), and Block Island (rocky) show the clearest contrasts demonstrating the effects of high-pressure hot-water washing. These observations and site-to-site contrasts provide confidence that conclusions based on the broader data set represent real differences.

This design assumed that site (habitat) groupings were similar enough to permit robust comparisons to identify major shifts in species dominance within assemblages. The authors believe that despite the limited replication of sites within each station category, the results accurately suggest the nature of continuing impacts and describe the direction of recovery. Validation of the 1990-92 results will occur within the sequence of longer-term monitoring and trend analyses.

In summary, this sample design was established to monitor long-term recovery trends at sites with known oiling and treatment history. It is well suited (by the number of replicate subsamples at each station) to compare pairs of stations representing sites with similar habitat but different oiling and/or treatment histories. However, because only a limited number of sites could be sampled in each habitat/oiling/treatment category, the design is less well suited for statistical inference regarding the generalized impacts of oiling and treatment over all habitats in Prince William Sound with similar oiling and treatment histories.

SITE CLASSIFICATION, OILING, AND TREATMENT HISTORY

Some 800 km of shoreline received sufficient oiling to require some form of shoreline cleanup or treatment in 1989 (Ciancaglini, 1991). Intensive efforts were made to verify the treatment history for each of the sites in this study (see Appendix Table A-1 in Houghton et al., 1993). Information used to document the site designations was compiled from Exxon and State of Alaska records of treatments applied to various "beach segments" and conversations with knowledgeable personnel in the field during 1989 (e.g., the authors, NOAA personnel, and field bosses for specific locations). However, each site sampled in the present study typically occupied only about 50 meters (m) along a given beach and thus represents only a small fraction of the shoreline segment in question as these segments could range from a few hundred meters to several kilometers in length.

For statistical testing and qualitative discussion purposes, sites, and in some cases stations within each habitat type were assigned to one of three categories to represent the range of possible stresses experienced in 1989 (stations at a given site may or may not be classified in the same category, depending on the known or inferred treatment history). Stations were classified as Category 1, 2, or 3 based on available information regarding habitat disturbance from oiling and high-pressure hot-water hydraulic treatment. Replicate stations were assigned to one of the following three site categories:

- Category 1: Unoiled in 1989—No significant oiling or treatment reported; considered reference stations.
- Category 2: Oiled in 1989—Untreated (set aside) or treated with cool-water flushes in 1989 and/or bioremediation in 1989, 1990, or 1991.
- Category 3: Oiled in 1989—Treated with high-pressure hot-water wash(es); most, if not all, were also bioremediated in 1989, 1990, and/or 1991.

Foster et al. (1990), Broman et al. (1983), and the Exxon-sponsored Omni-Barge and Corexit 9580 studies (Houghton et al., 1990a; Lees and Houghton, 1990; Lees et al., 1993) provided data on the severity of short-term impacts on intertidal biota from high-pressure hot-water wash treatments. Other forms of treatment (manual pickup, low-temperature flushes, and bioremediation) had far fewer effects on intertidal habitats and biota (personal observation and Foster et al., 1990) and thus were classified as Category 2 stations. This distinction was consistent with the broader study goal of assessing the effect of the dominant treatment method used in 1989 (high-pressure hot-water washes) on long-term recovery. Because most oiled sites in this study were treated with some form of bioremediation (nutrient enhancement) in one or more years, effects of bioremediation cannot be isolated within the sample design.

By special arrangement among responsible agencies, ten relatively small (< 900 m) lengths of shoreline were set aside and exempt from treatment. Four of these (two each in Herring Bay and Snug Harbor) were included in the study. There is no evidence that Category 2 sites in this study were high-pressure hot-water washed in 1989, but bioremediation was applied to the upper stations at the Snug Harbor sites in one or more of the post-spill years (ERC Environmental and Energy Services Company [ERCE] et al., 1990b).

Each intertidal station was classified as to the degree of oiling experienced in 1989. Oiling was typically very uneven vertically over the intertidal zone, and upper elevations were much more heavily oiled. As a result, oiling classifications for stations within a site usually differed. Moreover, the width of the oiled band on a shoreline has little effect on the specific intertidal assemblage at a station; what is important is the specific degree of oiling to which the plants and animals at that station are actually exposed (cf. Page et al., 1993).

The following oiling classifications were used in this study:

- Unoiled—No area of continuous oiling present at any time in 1989. Some sheens may have been present on adjacent waters. In 1990 no oiling was present except for possible widely scattered tar balls or spots of indeterminate origin.
- Lightly oiled—Patches of oiling in 1989 with fresh oil, mousse, or asphalt patches; cover generally less than 50 percent, or large areas of continuous sheen present on the beach. Little if any oil was visible in 1990. All stations at a site reported to have been oiled were considered to have been at least lightly oiled, even if no evidence of oil was ever gathered from that elevation.
- Moderately oiled—Near-continuous oiling in 1989 with fresh oil, mousse, or asphalt patches; cover often exceeding 50 percent and approaching 100 percent in some areas, but with relatively thin sheens; few areas of thick deposition (i.e., several millimeters (mm) or more). Usually some oil remained in these areas in 1990 in the form of coat or stain on upper rock surfaces or light sheens within soft sediments.
- Heavily oiled—Continuous oiling in 1989 with fresh oil, mousse, or asphalt patches; cover approaching or reaching 100 percent; some thick deposits (i.e., several mm or more). Considerable oil generally remained in these areas in 1990 in the form of coat or stain on upper rocky surfaces, or sheens and moist tar spots within soft sediments.

THE STUDY AREA

Prince William Sound is a protected fjord system located on the south-central coast of Alaska (Figure 1-2). Wave action from North Pacific storms is mediated by the outer line of islands. The winds, however, are only minimally abated by the low-lying peaks of those islands. This topography generates stormy seas and chop that strike exposed shorelines with high intensity wave action during storm events. Within embayments, wave energy may be minimal despite high wind forces because of limited fetch and frequent shifts in wind direction (Bascom, 1964; Lethcoe and Lethcoe, 1989). Fetch at specific locations within Prince William Sound, including several sites in this study, is provided by Michel and Hayes (1991). Tides are of the mixed semi-diurnal type; mean tide level is about 1.8 m, and extreme range is more than 5 m.

The study area encompasses most of central and southern Prince William Sound from Sheep Bay on the eastern mainland to Eshamy Bay and Bainbridge Passage on the western mainland (Figure 1-2). The sampling focused on the chain of islands stretching from Naked Island (in the central sound), south-southwest through the Knight Island group, to the islands protecting the southwest entrances to the sound. This portion of the Sound lay in the path of oil movement from the *Exxon Valdez*, and many beaches on these islands were oiled.

Unoiled beaches in Prince William Sound support biological communities relatively specific to and characteristic of a given habitat type and range of tidal elevation. Within these communities there are usually several species that, by virtue of their abundance and/or ecological roles (e.g., as an effective grazer or predator), exert a strong influence on other kinds of organisms found in the community. Throughout this report these taxa are termed community or assemblage "dominants."

REPORT ORGANIZATION

The 1992 report is organized into several chapters, each of which describes methods, results, and discussion of specific aspects of the study. Chapter 2 covers sediment and tissue hydrocarbon analyses, Chapter 3 reports on intertidal epibiota and associated physical and water quality measurements, Chapter 4 reports on intertidal infaunal communities and sediment grain size analyses, Chapter 5 contains results of mollusk studies, Chapter 6 provides results of several special studies, and Chapter 7 discusses major findings and conclusions. Acknowledgments, references for literature cited, and acronyms are also included.

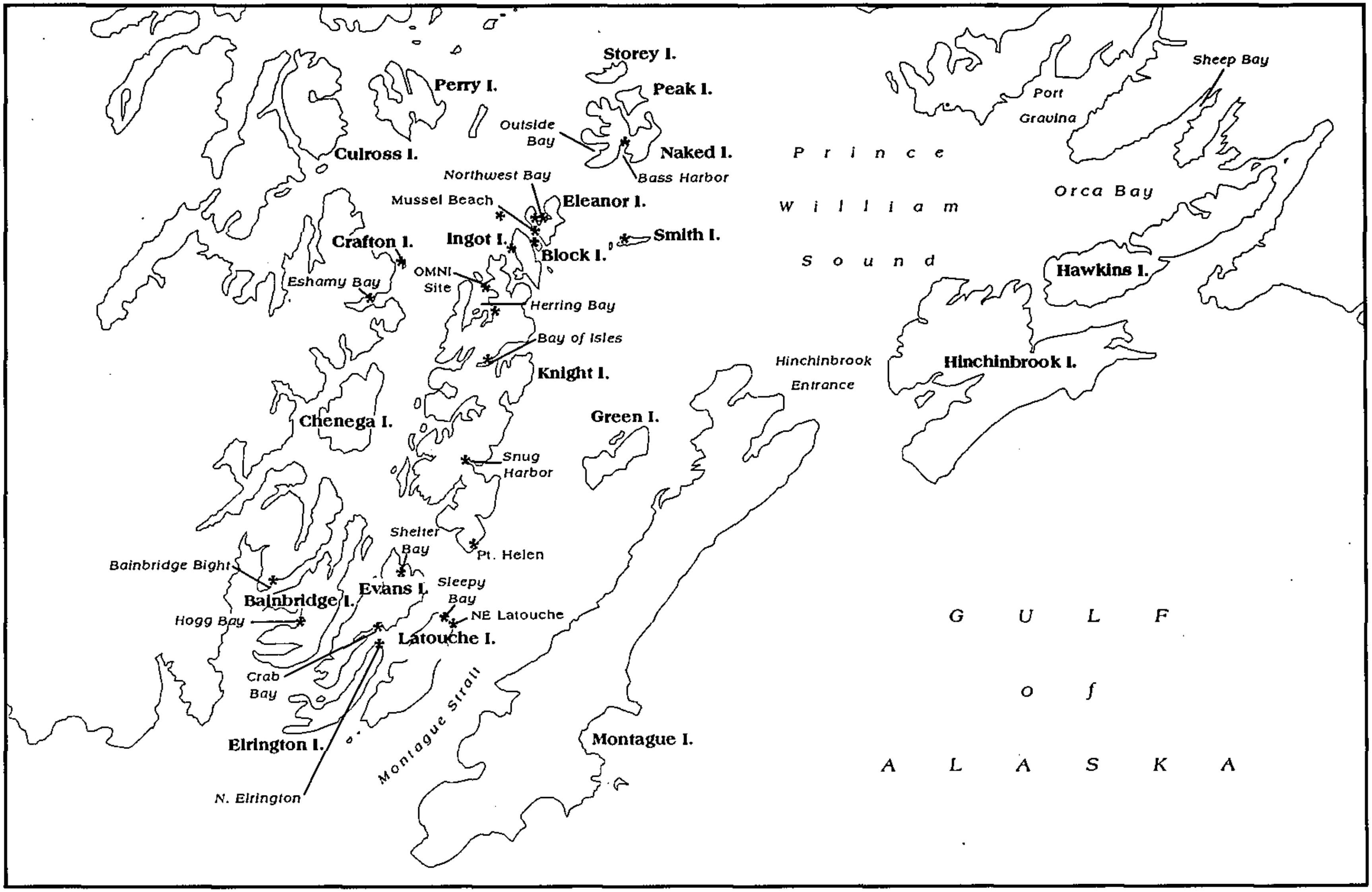

Figure 1-2. Prince William Sound study area and sampling locations (asterisks).

CHAPTER 2

SEDIMENT AND TISSUE HYDROCARBONS

INTRODUCTION

PAH levels in sediments at mixed-soft sites and in tissues of littleneck clams and mussels were analyzed in 1992. The average concentrations of individual PAH constituents are depicted in Appendix Figures B-1 to B-3 for sediments, B-4 to B-6 for littleneck clams, and B-7 to B-9 for mussels. Results of an experimental study using transplanted mussels and semipermeable membrane devices (SPMD) are found in Chapter 6.

METHODS

Sediment Hydrocarbons

Field Methods

Sediment samples for PAH analysis were collected at 22 sampling stations in June and July 1992. No attempt was made to sample bedrock or boulder surfaces. At the rocky and boulder/cobble locations, little surface oil was apparent in 1991 or 1992. The major sources of hydrocarbons were observed in depositional sediments; therefore, samples taken from sediment pockets among or under boulders or cobbles were assumed to be the best available indicators of maximum hydrocarbon concentrations to which the biota living nearby might be exposed.

Field sampling techniques were designed to ensure that no hydrocarbon contamination was introduced during collection. Field personnel wore disposable surgical gloves and used new wooden or Teflon spoons to place sediment samples in new precleaned glass jars. All equipment was changed between samples. At most stations the sediment sample was composited from surface sediments scooped to about three cm deep at five randomly chosen locations along each transect. Sampling points were coincident with the five infaunal cores along the established mixed-soft transects. At some stations a discrete sediment sample (i.e., not composited) was collected adjacent to each of the five infaunal coring locations for direct correlation with infaunal variables. Thus, hydrocarbon samples were collected from the same tidal levels as the biological samples. All samples were frozen aboard the vessels and shipped frozen to the laboratory.

Laboratory Methods

Sediment hydrocarbon analyses were performed at the Institute for Environmental Studies (IES), Louisiana State University, Baton Rouge, Louisiana. Methods were modified from procedures of Krahn et al. (1988a). Sediment samples were weighed into 600-milliliter (ml) beakers for extraction. Approximately 100 cubic centimeters (cc) of material was extracted for each sample. The samples were dried prior to extraction by the addition of anhydrous sodium sulfate (Na_2SO_4). Sodium sulfate not only removed any water as an extraction interference but also enhanced the extraction of weathered oil residue from the pebbles and gravel by acting as an abrasive. Surrogate standards *d*-10-acenaphthylene, *d*-10-phenanthrene, and *d*-14-terphenyl were added. Samples were extracted three times using nanograde hexane solvent and a bath sonication- technique. The extracts were combined and then reduced in volume by a combination of rotary-evaporation and solvent reduction under a gentle stream of high purity nitrogen (nitrogen blow-down). The final sample volume varied between 1 ml and 150 ml depending on the degree of contamination. The extracts were analyzed by gas chromatography/mass spectrometry (GC/MS) using a Hewlett Packard 5890 gas chromatograph (GC) equipped with a DB-5 high- resolution capillary column directly interfaced to a Hewlett Packard 5970B mass spectrometer (MS). The GC was optimized to provide the required degree of separation (i.e., baseline resolution between nC-17 and pristane). The GC was operated in the temperature program mode with an initial column temperature of 55°C for 3 minutes, then increased to 290°C at a rate of 6°C per minute, and held at the upper temperature for 17 minutes. The MS was operated in the selective ion mode to enhance quantitative analyses. The injection temperature was held constant at 250°C, and only high temperature, low thermal bleed septa were used. The interface to the MS was maintained at 280°C.

At the beginning of each analysis period, the MS was tuned to perfluorotributylamine. Quantitative analysis was by an internal standard technique using authentic standards for the nonalkylated PAHs with the exception of naphthobenzothio–phene, which was estimated using the response of dibenzothiophene. The alkylated homologs were calculated using the nonalkylated parent. The following internal standards were co-injected: *d*-8-naphthalene, *d*-10-anthracene, *d*-12-chrysene, and *d*-12-perylene. Values reported as total PAHs are the totals of target analytes (listed in Table 6-10).

Tissue Hydrocarbons

Field Methods

Tissue samples for PAH analysis were collected from populations of mussels and littleneck clams by field personnel wearing surgical gloves. The number of organisms sampled varied according to the size of the animals, but a minimum of 10 grams (g) of wet tissue was collected to permit replicate chemical analyses. For example, sample sizes for mussels usually ranged between 20 and 35 individuals. The entire sample of whole individuals for each species was carefully wrapped in aluminum foil. The samples were then placed in labeled polyethylene bags and frozen for transport to the laboratory.

Laboratory Methods

Tissue PAH analyses also were performed by IES. Methods were modified from the procedures of Krahn et al. (1988a). Only samples of mussels and littleneck clams were analyzed in 1992. The tissues samples were carefully removed from their shells, thoroughly rinsed with deionized water, and refrigerated in solvent-rinsed jars with Teflon-lined caps before further sample preparation. If delays of more than two to three days were expected, the samples were frozen. For analysis, a small aliquot (3 to 5 g) of the homogenized tissue was added to 40-ml precleaned and solvent-rinsed vials. The samples were digested overnight by the addition of a single pellet of potassium hydroxide (KOH). To enhance the digestion, the samples were sonicated and swirled periodically. The samples were then spiked with the same surrogate standard suite used for sediment analyses. The samples were dried with anhydrous sodium sulfate until they achieved the consistency of dry sand. They were then extracted three times with dichloromethane (DCM). The extracts were combined into a single rotary-evaporation flask and reduced in volume to less than 4 ml. At this time the sample extract was transferred into 4-ml vials and further reduced in volume by nitrogen blow-down. The solvent was exchanged into hexane and reduced to 100 µl.

Sample fractionation, or cleanup, was required to enrich the target analytes and at the same time exclude matrix interferences. Sample fractionation was performed using silica-gel/alumina columns. The columns were calibrated such that the desired analytes were eluted from the column in the F-2, or aromatic, fraction. This fraction was eluted into conical 4-ml volumetric vials and reduced to a final extract volume of 0.1 ml before instrumental analysis. The target analytes were quantified by an internal standard method and corrected for recovery using surrogate standards. Values reported as total PAHs are the totals of the target analytes (Table 6-10).

Lipid weights were determined by preparing the sample as above except for fractionation. The weight of the solvent extract was determined by a gravimetric analysis (oil/grease analysis). The results from these analyses are crude and subject to a variety of interferences that may overestimate the true lipid weight.

Dry weights were determined by weighing a small amount of the homogenized tissue on a preconditioned, prenumbered, and preweighed tin. The tin was placed into a drying oven at 90°C for 24 hours, then reweighed.

Data Management and Analyses

All field data and a portion of the laboratory data were double entered and/or 100 percent verified prior to analysis. Errors identified were corrected based on examination of original field or laboratory notes. Remaining laboratory data were directly entered in the laboratory and did not require verification.

Several conventions were employed to calculate averages used in elevation/ treatment comparisons of summed target PAH values. Generally, the sample taken at each station was a composite from five positions along the sampling transect. The value used to represent each station in elevation/treatment comparisons was the average of all 1992 results available for that station. For purposes of laboratory QA/QC, replicate analyses were sometimes run on samples; for calculation of summary statistics, these replicates were averaged and treated as a single value. In short, to calculate statistics for elevation/treatment comparisons, all results for a station were averaged to obtain a single value that was used as the representative concentration for a specific station/treatment cell.

Where the concentration of a constituent was below detection limits, a value of zero was arbitrarily assigned for calculation of total PAHs. When plotting GC/MS histograms depicting the concentrations and distribution of the constituents, however, a value of 0.01 parts per billion (ppb) was arbitrarily assigned to constituents with values below detection limits to allow use of a $\log_{10}$ transformation of the data.

RESULTS

Sediment Hydrocarbons

In 1992 analytical effort for sediment PAH analysis was directed toward lower intertidal samples, to provide a basis for comparison to infaunal results. PAHs were measured in sediments from the lower intertidal zone at 12 sites representing all three site categories (Table 2-1). The average concentration of total target PAHs for these samples was 0.088 ± 0.21 parts per million (ppm). Generally, concentrations were highest at Category 2 sites and lowest at Category 1 sites; intermediate concentrations occurred at Category 3 sites. PAH concentrations varied considerably at Category 2 and 3 sites and were highest by an order of magnitude at the Category 2 Block Island lower station.

Distribution of homologs in the PAHs from the various sites was examined to provide insights into the source and degree of weathering of the hydrocarbons at each site. Generally, with the exception of Block Island, the quantity and condition of the hydrocarbons in sediments was quite similar in the samples analyzed from sites in both Category 2 and 3. The predominant PAH compounds in sediments at all sites except Block Island (in decreasing order of abundance) were pyrenes, naphthobenzothiophenes, chrysenes, and phenanthrenes (Table 2-2). The relatively low concentrations of naphthalenes, fluorenes, and dibenzothiophenes suggest that the hydrocarbons at these sites were fairly highly weathered. Moreover, the relatively elevated concentrations of the nonalkylated four- and five-ring PAHs such as fluoranthene, pyrene, benzo(a)anthracene, chrysene, and benzo(a)pyrene suggest a strong pyrogenic component in the hydrocarbons at many of the sites.

In contrast, the dominance of naphthalenes, fluorenes, dibenzothiophenes, and phenanthrenes at Block Island indicates that the hydrocarbons observed in the sediments there are less weathered and are more representative of the crude oil spilled (Table 2-2). Of the sites sampled in 1992, Block Island sediments clearly contained the highest concentrations of residual hydrocarbons, which were conspicuous when the sediment was disturbed.

The results suggest that the hydrocarbons observed at the control sites were predominantly pyrogenic or residual from refined fuel oil (Appendix Figure B-1). Concentrations of hydrocarbons at Crab Bay (Table 2-1) probably reflect the proximity of the site to the village of New Chenega and its associated sources of hydrocarbons.

PAHs in sediments from Category 2 sites ranged from below detection limits at Herring Bay to 0.78 ppm at Block Island (Table 2-1), where in 1992, dark brown oil and heavy sheens were still evident in shallow excavations. PAHs in sediments from Block Island (as described above) were less weathered than those observed at other Category 2 sites (i.e., Ingot Island, Mussel Beach, and Snug Harbor; Appendix Figure B-2).

The degree of weathering in PAHs at Category 3 sites also varied substantially (Appendix Figure B-3). The paucity of lighter fractions at Northwest Bay West Arm and Shelter Bay indicates that considerable weathering has taken place at these sites. The similarity in composition of the hydrocarbons at these two sites is striking. Although the hydrocarbons at Sleepy Bay appears to be less weathered, the presence of fluoranthene, pyrene, benzo(a)anthracene, and chrysene, however, indicates that these sites have been exposed to appreciable quantities of combustion by-products.

Littleneck Clam Tissue Hydrocarbons

Littleneck clam (*Protothaca staminea*) soft tissues were sampled at 11 lower mixed-soft habitats in July 1992. The average concentration of target PAHs in littleneck tissues was 0.43 ±1.08 ppm (dry-weight basis; Table 2-1). Patterns among the treatment categories were similar to those described for the sediments—that is, highest tissue concentrations occurred at Category 2 sites (dominated by Block Island, which also had the highest sediment concentrations); intermediate concentrations occurred at Category 3 sites; and lowest levels were at Category 1 sites. Generally, variability within the categories was greater in littlenecks than in sediments.

Table 2-1 Concentration of PAH (ppm) for sediments and tissues from Prince William Sound, 1992.

	Treatment Category	Sediment wet weight	*Mytilus* dry weight	*Protothaca* dry weight
Bainbridge Bight low mixed soft	Category 1		0.120	0.017
Bass Harbor upper boulder	Category 1		0.095	
Crab Bay mid mixed soft	Category 1		0.200	
Crab Bay low mixed soft	Category 1	0.006		0.018
Eshamy Bay mid rock	Category 1		0.140	
Hogg Bay upper rock	Category 1		0.086	
Outside Bay mid mixed soft	Category 1		0.540	
Outside Bay low mixed soft	Category 1	0.002		
Sheep Bay mid mixed soft	Category 1		0.270	
Sheep Bay low mixed soft	Category 1	0.000		0.041
Bay of Isles mid rock	Category 2		0.120	
Block Island low mixed soft	Category 2	0.780	8.900	3.500
Crafton Island mid mixed soft	Category 2		0.300	
Herring Bay mid mixed soft	Category 2		0.600	
Herring Bay mid mixed soft	Category 2		0.640	
Herring Bay low mixed soft	Category 2	0.000		
Ingot Island mid mixed soft	Category 2	0.015	0.450	
Mussel Beach mid soft	Category 2		0.440	
Mussel Beach low soft	Category 2	0.023		0.130
Snug Harbor mid rocky	Category 2		0.860	
Snug Harbor mid mixed soft	Category 2		0.038	
Snug Harbor low mixed soft	Category 2	0.043		0.019
Block Island mid rocky	Category 3		2.300	
Block Island mid mixed soft	Category 3		0.650	
Elrington East upper mixed soft	Category 3		2.300	
Elrington East mid mixed soft	Category 3		0.330	
Elrington East low mixed soft	Category 3	0.048		0.190
Elrington West mid rocky	Category 3		0.880	
Elrington West low mixed soft	Category 3			0.100
Ingot Island mid rocky	Category 3		2.100	
NE Latouche mid boulder	Category 3		0.250	
NW Bay Rocky Islet mid rocky	Category 3		1.200	
NW Bay W Arm mid mixed soft	Category 3		0.370	
NW Bay W Arm low mixed soft	Category 3	0.020		0.082
Herring Bay Omnibarge site mid	Category 3		0.400	
Point Helen mid boulder	Category 3		0.630	
Shelter Bay mid mixed soft	Category 3		0.190	
Shelter Bay low mixed soft	Category 3	0.019		0.008
Sleepy Bay mid mixed soft	Category 3		0.140	
Sleepy Bay low mixed soft	Category 3	0.099		0.630
New Chenega dock floats	Special collection		5.700	
Category 1 Average		0.0024 (n=3)	0.21 (n=7)	0.025 (n=3)
Category 2 Average		0.17 (n=5)	1.4 (n=9)	1.2 (n=3)
Category 3 Average		0.047 (n=4)	0.90 (n=13)	0.20 (n=5)
Category 1 SD		0.002	0.148	0.011
Category 2 SD		0.304	2.672	1.615
Category 3 SD		0.236	1.857	0.222
Category 1 Coefficient of Variation-%		98	72	44
Category 2 Coefficient of Variation-%		177	195	133
Category 3 Coefficient of Variation-%		70	87	110
Overall Mean		0.09	0.88	0.43
Overall SD		0.210	1.637	0.985
Overall Coefficient of Variation-%		240	186	229

Table 2-2 Distribution of major PAH groups in sediment and mussel tissue, 1992.

PAH group	Sediment at All Sites Except Block Island wet weight (ppm)	Sediment at Block Island lower wet weight (ppm)	*Mytilus* All Sites Except Block Island dry weight (ppm)	*Mytilus* Block Island lower dry weight (ppm)
% Naphthalenes	1.5	25.50	5.8	4.3
% Fluorenes	9.0	24.70	15.1	17.6
% Dibenzothiophenes	8.3	18.90	11.5	21.0
% Phenanthrenes	11.3	19.50	26.8	12.3
% Anthracene	0.3	0.02	0.5	11.2
% Naphthobenzothiophenes	14.0	2.30	14.1	11.2
% Fluoranthene	3.3	0.20	1.7	2.8
% Pyrenes	22.0	5.60	4.7	6.5
% Benzo(a)anthracene	1.6	0.05	1.0	4.0
% Chrysenes	13.6	2.40	10.5	4.2
% Benzo(b)fluoranthene	3.3	0.20	1.5	0.8
% Benzo(e)pyrene	3.2	0.20	1.3	0.5
% Benzo(a)pyrene	2.2	0.07	1.7	0.3
% Perylene	0.8	0.04	1.4	0.3
% Indeno(1,2,3-c,d)pyrene	1.0	0.00	0.7	1.0
% Dibenzo(a,h)anthracene	0.5	0.00	0.8	1.0
% Benzo(g,h,i)perylene	4.1	0.20	1.0	1.0
Average Total Concentration (ppm)	0.025	0.78	0.068	8.9

At the Category 1 sites the concentrations of PAHs in littlenecks ranged from 0.017 ppm (dry) to 0.041 ppm; all are "not contaminated" according to criteria of the interagency program to monitor the effects of *Exxon Valdez* oil on subsistence foods (Brown et al., 1993). Most PAHs in clams from this category were chrysenes and pyrenes, but dibenzo(a,h)anthracene and C-3 dibenzothiophene were the most abundant analytes in Bainbridge Bight clams, and C-2 phenanthrene was the most abundant in Crab Bay clams (Appendix Figure B-4).

At Category 2 sites the concentrations of PAHs in littlenecks ranged from 0.019 ppm (dry; Snug Harbor) to 3.49 ppm (dry; Block Island). The Block Island clams would be considered "moderately contaminated" by the criteria of Brown et al. (1993). Clams from Category 2 sites had a wider range of hydrocarbon distribution than those from Category 1 sites. Significant contributions of the dibenzothiophenes were found at all sites. Concentrations of fluorenes were high at Mussel Beach and Snug Harbor, and naphthalenes were present only at Block Island (Appendix Figure B-5), the site with the highest concentrations of these relatively more volatile compounds remaining in the sediments in 1992 (Appendix Figure B-2).

At Category 3 sites the PAH concentrations ranged from 0.008 ppm (dry; Shelter Bay) to 0.628 ppm (dry; Sleepy Bay); Shelter Bay clams would be considered "not contaminated," and those from other Category 3 sites would be considered "minimally contaminated" according to the criteria of Brown et al. (1993). Clams from previously sampled Category 3 sites had hydrocarbon distributions that are in some respects similar to hose from Category 1 sites with heavier pyrenes, chrysenes, and perylenes in highest concentrations. At the two sites first sampled in 1992, North Elrington East had a strong component of pyrenes, phenanthrenes, and anthracene, and North Elrington West had two fluorenes among the dominant analytes (Appendix Figure B-6).

Mussel Tissue Hydrocarbons

Mussel tissues from 28 sites were analyzed for PAHs in 1992. The overall average concentration of PAHs in these tissues was 0.88 ± 1.64 ppm dry weight (Table 2-1). Patterns among the treatment categories were similar to those described for the sediments and littleneck tissue (i.e., highest tissue concentrations occurred at the Category 2 sites; intermediate levels occurred at Category 3 sites, and lowest levels were observed at Category 1 sites). Generally, variability within the categories as measured by the coefficient of variation was similar in mussels and sediments and was highest for Category 2 sites.

Distribution patterns for PAHs in mussel tissues were relatively similar among all sites (Table 2-2; Appendix Figures B-7 through B-9). Generally, phenanthrenes, fluorenes, naphthobenzothiophenes, and dibenzothiophenes, in decreasing order of abundance, were the predominant compounds in mussel tissues from all sites excluding Block Island (Table 2-2). The least weathered tissue hydrocarbons were found at Block Island, where highest concentrations of relatively unweathered sediment hydrocarbons were found. The relatively higher proportion of heavier fractions in tissues may reflect the weathering process and/or selective depuration of lighter fractions. Many of the mussel populations appear to have accumulated appreciable concentrations of compounds that indicate exposure to fuels (dibenzothiophenes and phenanthrenes) and/or combustion products (e.g., fluoranthene, pyrene, benzo(a)anthracene, and chrysene).

Rocky Habitat Oil Cover

Percent oil cover in 0.25-m^2 quadrats was estimated at all rocky sites sampled from 1990 to 1992. Most oil was found at the upper elevations (Figure 2-1), where Category 2 and Category 3 sites had similar oil cover through all years except in May 1991, when a high cover of black oil crust was observed at the Herring Bay site (Appendix Table C-1-1). At other sites, where this black crust was examined microscopically, it was found to be a combination of oil and blue-green algae; thus, the high oil cover at Herring Bay may have been inaccurate. The middle elevation had a higher oil cover at Category 3 sites than at Category 2 sites in 1990, but by 1991 oil cover was equal at both of these categories. By 1992 visible oil cover was negligible at all rocky sites.

DISCUSSION

As has been previously discussed (Houghton et al., 1993) the patchiness in environmental concentrations of PAHs complicates interpretation of chemistry results and trends in those results. Physical differences in the environment and micro environment where oil is stranded also influence how the oil weathers with time. The inherent variability associated with PAH residues in sediments requires that chemistry results for such environmental assessments as this be interpreted cautiously. It is clear that the data set is of limited utility for detecting or describing changes in hydrocarbon concentrations, even at sites that were sampled in all three years.

In order to assess trends in hydrocarbon degradation, sediment PAH data for 1990-92 have been summarized in Table 2-3. Higher concentrations were observed at 71 percent of the 31 stations sampled in both 1990 and 1991, suggesting that hydrocarbon concentrations were higher in 1991 than in 1990.

In view of findings in our 1990 and 1991 studies that sediment PAH concentration appeared influenced by elevation (Houghton et al., 1991a; 1993), the distribution of the sample stations among tidal levels was compared and found to differ considerably in 1992 from that in the two prior years. In 1990 and 1991 upper, middle, and lower intertidal levels were all represented, but middle and lower levels represented about 42 to 45 percent of the samples analyzed, respectively. In contrast, in 1992 all samples analyzed were from the lower intertidal zone.

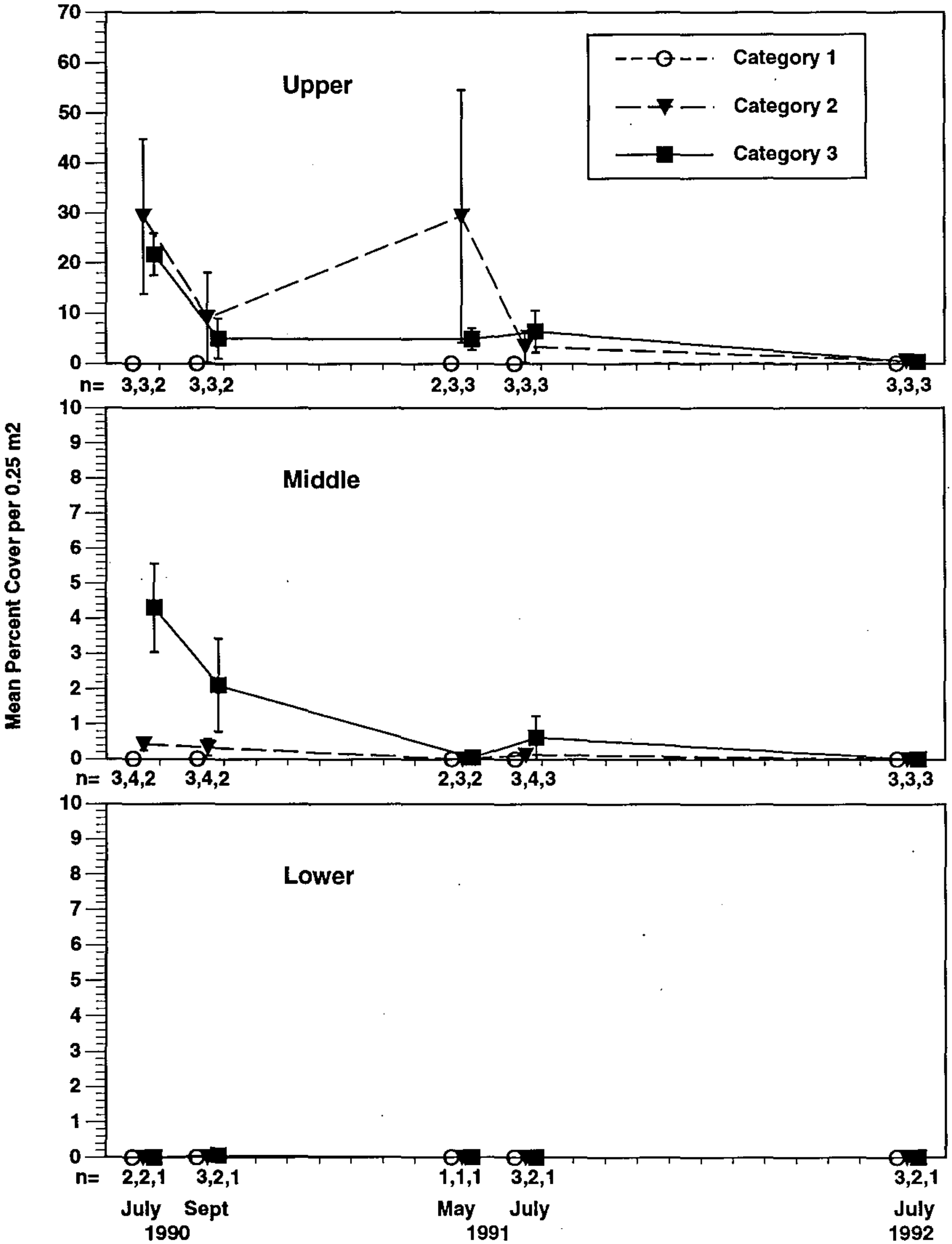

Figure 2-1. Mean percent cover (± 1 SE) of oil cover from rocky sites, 1990-92. Number of stations sampled (n) shown below axis. Note change of scale in upper.

To eliminate the potential effects of this disproportionate distribution, the authors compared only data from the lower intertidal stations at which sampling was repeated in at least two of the three years. In addition, the data from the lower rocky site at Northwest Bay Rocky Islet have been eliminated as outliers. Resulting comparisons of lower intertidal data suggest an explanation for the pattern discussed above that highest concentrations of PAHs in intertidal sediments occurred in 1991. For the eight stations where samples were analyzed in all three years, PAH concentrations appeared to increase substantially in 1991, but to decline to approximately 1990 levels in 1992 (means of 0.092, 0.51, and 0.12 ppm in 1990, 1991, and 1992, respectively). Differences among years were significant ($p < 0.1$, Friedman nonparametric analysis of variance [ANOVA]). In the 12 cases where samples were analyzed in both 1990 and 1991, PAH concentrations appeared to increase moderately in 1991 (0.25 to 0.48 ppm; $p > 0.1$, paired-sample test). In the ten cases where stations could be compared in 1990 and 1992, concentrations were fairly similar (0.092 and 0.10 ppm; $p > 0.1$, paired-sample test). Finally, in the nine instances where data exist for the same stations in 1991 and 1992, concentrations appeared to decline moderately (0.45 to 0.11 ppm; $p < 0.1$, paired-sample test).

Since the oil spill, it is possible that PAHs have moved downward from upper levels of the intertidal zone where initial oiling was heaviest. The rate of movement at specific sites has probably varied according to the degree of treatment or exposure experienced at each site. A possible explanation for the temporal pattern reported above is that the peak of the PAH pulse was passing through the lower intertidal zone in 1991 and had passed into the subtidal zone in 1992.

PAHs in the lower mixed-soft sediments in 1992 exhibited a highly significant negative correlation with percent silt in the sediment ($r = -0.78$, $p < 0.005$). Thus, areas characterized by higher proportions of fine sediment had lower concentrations of hydrocarbons than areas where sediment was coarse. This point is relevant for two reasons. First, organic compounds typically tend, as a rule, to be associated with finer sediments. At study sites sampled in Prince William Sound in 1992, both TOC and nitrogen exhibited marginal correlations with percent silt. Second, the sites with lowest proportion of silt were the Category 3 sites (i.e., the sediments had been subjected to washing with pressurized water, a process that tend to remove the fines from sediments in the area treated).

Concentrations of target PAHs in littleneck clams dropped substantially from 1991 to 1992 at all stations sampled in both years except Sheep Bay (Category 1) and Block Island (Category 2), where there was little change. At Block Island PAHs in sediments remained relatively high in 1992 (0.78 ppm wet), and tissue concentrations in littlenecks (0.37 ppm wet) declined somewhat (by 26 percent) from those in July 1991 (0.50 ppm wet). Concentrations in clam tissue at the three Category 3 sites sampled in both years declined by at least 54 percent in 1992.

Table 2-3 Summary of sediment PAH data, Prince William Sound, 1990-92.

Location	Treatment Category	Elevation	Substrate	Total PAH (wet ppm) 1990	1991	1992
Bainbridge Bight	1	low	mixed soft		0.0005	
Bass Harbor	1	mid	boulder/cobble	0.0005	0.0060	
Crab Bay	1	low	mixed soft	0.0032		0.0056
Outside Bay Site 1	1	low	mixed soft	0.0001	0.0004	0.0016
Sheep Bay	1	low	mixed soft	0.0004		0.0000
Bay of Isles	2	mid	rocky		4.4000	
Bay of Isles	2	low	mixed soft	2.0000	1.1000	
Block Island	2	low	mixed soft	0.4800	3.8000	0.7800
Crafton Island	2	mid	mixed soft	0.0170	0.0950	
Crafton Island	2	low	mixed soft	0.0880	0.3300	
Herring Bay	2	mid	mixed soft	0.0009	0.0011	
Herring Bay	2	mid	rocky	8.1000	0.5900	
Herring Bay	2	low	mixed soft	0.0005	0.0045	0.0000
Herring Bay	2	low	rocky		0.0660	
Mussel Beach	2	mid	mixed soft	0.1400	0.4900	
Mussel Beach	2	low	mixed soft	0.0490	0.0820	0.0230
Snug Harbor	2	upper	mixed soft	0.0410	0.0680	
Snug Harbor	2	upper	rocky	16.0000	11.0000	
Snug Harbor	2	mid	mixed soft	0.0920	0.1300	
Snug Harbor	2	mid	rocky	20.0000	0.4200	
Snug Harbor	2	low	mixed soft	0.0024	0.0055	0.0430
Snug Harbor	2	low	rocky	0.0130	0.2100	
Block Island	3	upper	mixed soft	2.5000	0.8900	
Elrington Island East	3	low	mixed soft			0.0480
Ingot Island	3	upper	rocky		0.0450	
Ingot Island	3	mid	rocky		7.2000	
Ingot Island	3	low	mixed soft		0.0250	0.0150
NE Latouche Island	3	mid	boulder/cobble	0.0031	0.0700	
Northwest Bay Islet	3	upper	rocky	0.1400	0.2200	
Northwest Bay Islet	3	supralit	rocky		38.0000	
Northwest Bay Islet	3	mid	rocky	1.4000	0.1700	
Northwest Bay Islet	3	low	rocky	64.0000	5.8000	
Northwest Bay West Arm	3	mid	mixed soft	0.3300	6.7000	
Northwest Bay West Arm	3	low	mixed soft	0.0058	0.0300	0.0200
Point Helen	3	mid	boulder/cobble	0.0034	10.0000	
Point Helen	3	low	boulder/cobble		0.0026	
Shelter Bay	3	mid	mixed soft	15.0000	0.0540	
Shelter Bay	3	low	mixed soft	0.3700	0.0270	0.0190
Sleepy Bay	3	mid	mixed soft	0.0290	0.3900	
Sleepy Bay	3	low	mixed soft	0.0051	0.1200	0.0990
Smith Island	3	upper	boulder/cobble		0.0940	
Smith Island	3	mid	boulder/cobble	0.0670	0.7400	
Smith Island	3	low	boulder/cobble	0.0024	0.0240	
Selected Average*				0.0920	0.4550	0.0880

* Only sites with data in 1992 were used

While PAH concentrations in mussel tissue have been measured in all three years of this study only at Eshamy Bay, a Category 1 site, the data for 1990 and 1992 suggest that tissue PAHs have declined substantially over that period at other sites as well (Table 2-4). Overall, tissue PAHs declined from 4.2 to 0.46 ppm dry weight at sites for which samples were analyzed in both 1990 and 1991. They declined by about 80 percent at Category 1 and 2 sites, and by more than 90 percent at Category 3 sites. In sharp contrast to the trend in tissue PAHs at most sites, tissue PAHs in mussels from the middle intertidal rocky station at Block Island did not decrease; continued exposure to hydrocarbons remaining in the sediments can be inferred (Table 2-1).

Mussel tissue samples collected from sites near Seward and from the dock in New Chenega were analyzed in 1991 and 1992, respectively (Tables 2-1 and 2-4). Hydrocarbon contamination in samples from these unoiled sites was considerably higher than average contamination in all treatment categories except Category 3 in 1990. Values observed were similar to those at more contaminated sites in 1991 and 1992 (e.g., Smith Island, Block Island). Moreover, the distribution of the PAH homologs was quite similar among the samples from Seward and New Chenega and those from the remote and highly contaminated sites (e.g., Block Island low soft in Appendix Figure B-8). A striking feature of most of the hydrocarbons found in mussel tissues with the highest PAH concentrations, whether from remote and oiled sites or from sites in the vicinity of boat operations, is the presence of appreciable concentrations of a variety of naphthalenes.

Applying an average value of 88 percent moisture in mussel tissue determined in this program to results obtained at various periods in 1989 and 1990 by Short and Rounds (1993a), PAH concentrations in mussel tissue determined by those researchers were comparable in magnitude to those found in one study (Table 2-4). For example, Short and Rounds observed concentrations of approximately 45 ppm dry weight in caged mussels suspended at a one-m depth in the water column in Herring Bay to two months following the spill. In 1990 this study reported concentrations of 42 and 82 ppm dry weight in mussels from the intertidal zone at Northeast Latouche Island and Smith Island, respectively (Table 2-4).

The concentration of approximately 0.08 ppm dry weight reported by Short and Rounds (1993a) for Olsen Bay, their reference site, is representative of the range of concentrations observed at reference sites in this study in 1990 and 1992. Only three of fifteen PAH measurements for reference sites in this study had concentrations this low (i.e., hundredths of a ppm), however. This independent reference value suggests that mussels from several reference sites in this study are exposed to low but detectable levels of hydrocarbon contamination, and indicates that a background level of general contamination, probably not associated with the spill, exists at sites throughout the study area.

Table 2-4. Summary of mussel tissue PAH data from biological sampling sites in Prince William Sound, 1990-92.

Location	Treatment Category	Total PAH (dry ppm)		
		1990	1991	
Samples from Remote Sites				
Bainbridge Bight low mixed soft	1			0.120
Bass Harbor upper boulder	1	6.500		0.095
Crab Bay mid rocky	1	0.014		
Crab Bay mid mixed soft	1	0.340		0.200
Eshamy Bay mid mixed soft	1	1.500	0.760	0.140
Hogg Bay upper rock	1	0.200		0.086
Outside Bay mid mixed soft	1	0.380		0.540
Sheep Bay mid mixed soft	1	0.160		0.270
Bay of Isles mid rock	2	1.100		0.120
Block Island low mixed soft	2			8.900
Crafton Island mid mixed soft	2	0.540		0.300
Herring Bay mid gravel/cobble	2	4.400		0.600
Herring Bay mid mixed soft	2			0.640
Ingot Island mid mixed soft	2			0.450
Mussel Beach mid soft	2	0.730		0.440
Snug Harbor Rock	2	1.200		0.860
Snug Harbor Soft	2	0.540		0.038
Block Island mid rocky	3	2.600		2.300
Block Island mid mixed soft	3			0.650
Elrington East upper mixed soft	3			2.300
Elrington East mid mixed soft	3			0.330
Elrington West mid rocky	3			0.880
Herring Bay Omnibarge site mid	3			0.400
Ingot Island mid rocky	3			2.100
Northeast Latouche	3	42.000		0.250
Northwest Bay Rocky Islet	3	3.400		1.200
Northwest Bay West Arm	3	0.240		0.370
Point Helen mid boulder	3	3.200		0.630
Shelter Bay mid mixed soft	3	5.900		0.190
Sleepy Bay mid mixed soft	3	5.100		0.140
Smith Island	3	82.000	5.800	
Samples from Vicinity of Towns				
Seward - May 1991			6.200	
New Chenega dock pilings				5.700
Mean	Category 1	1.5	n=7	0.22
	Category 2	1.4	n=6	0.39
	Category 3	8.9	n=7	0.73
Standard Deviation	Category 1	2.28		0.16
	Category 2	1.36		0.28
	Category 3	13.61		0.73
Coefficient of Variation (CV)	Category 1	150		70
	Category 2	96		71
	Category 3	153		100
Overall Summaries	Mean	4.21		0.46
	SD	9.13		0.52
	CV	217		113

In 1990 the highest concentration reported by Short and Rounds (1993a) was approximately 2.2 ppm dry weight in Herring Bay and Snug Harbor. We found similar concentrations at sites in all three treatment categories in that year (Table 2-4). Generally, the concentrations reported by Short and Rounds (1993a) are toward the low end of the ranges observed in this study. Considering that a major source of PAH contamination in the Sound is residual oil still entrained in the shoreline, it is reasonable to expect reductions in contamination with increasing distance offshore from the contamination source.

Relationships among PAHs in sediment and mussel and littleneck clam tissues from the same site were examined by Pearson product-moment correlation. PAH concentrations in clams and sediments were significantly correlated ($r = 0.62$, $p < 0.1$), but this relationship was not significant for mussels. PAH concentrations were highly correlated in mussels and clams from the same site, however ($r = 0.74$, $p < 0.05$). This suggests that hydrocarbon concentrations in clams are more closely linked to local conditions than were those in mussels. The finding that PAH concentrations in clams exhibited a significant negative correlation with percent silt ($r = -0.61$, $p < 0.1$) is very likely related to the finding reported above of a negative correlation between sediment PAH and percent silt. An unusual additional finding was that PAHs in clam tissues correlated significantly with salinity ($r = 0.66$, $p < 0.1$).

Bioconcentration factors for mussels and littleneck clams exhibited a strong positive correlation with each other ($r = 0.85$, $p < 0.01$); resultant PAH concentrations in the clams were consistently lower than those in mussels from the same site, however. Moreover, the PAH homologs in mussel tissue appear to be more representative of the PAHs in the sediments than are those in the littleneck clam. Comparison of the compounds found in mussels and clams from Bainbridge Bight and Northwest Bay West Arm shows no compounds in common. In view of the generally closer proximity of the clams to contaminated sediments, these findings may reflect differences in feeding strategy, or could imply that the clams filter less water, depurate hydrocarbons more rapidly, or metabolize hydrocarbons more effectively than the mussels. Tanacredi et al. (1991), however, reported that the clam *Mercenaria mercenaria*, a venerid closely related to the littleneck clam, depurated at a relatively slow rate in laboratory tests. Alternatively, this lesser uptake by clams may simply reflect the fact that they were typically collected from lower portions of the beach than were mussels and, thus, had less frequent exposure to surface sheens. Without further information the cause for the differential uptake by these two mollusks cannot be identified.

PAH concentration in mussel tissues averaged about 1,600 times the wet sediment concentrations for the same site. For littleneck clams the bioconcentration factors averaged 100 times wet sediment concentrations. Based on data reported by Short and Rounds (1993a, b), bioconcentration factors in mussels suspended in the water column in Herring Bay for several months following the spill appeared to range from about 600 to 8,600.

Bioconcentration factors for PAHs in tissues of both mussels and littleneck clams exhibited significant negative correlations with sediment concentrations of PAHs ($r = 0.89$ and 0.70; $p < 0.001$ and < 0.1, respectively). The regression equations relating PAHs in mussel and clam tissue (Y) to sediment PAH (X) are:

$$\log Y_{mussel} = -0.166 - 0.895(\log X) \quad \text{and} \quad \log Y_{clam} = -0.349 - 0.589(\log X)$$

The interactions of shoreline treatment with TOC may be a factor influencing these negative correlations. Weston (1990) reported that assimilation rates of PAH increased in a nonlinear manner as TOC in sediments was reduced. PAH assimilation rates were fairly stable at 1 to 2 percent but were dramatically higher at 0.3 percent TOC. In our 1992 data, average TOC concentration at Category 2 sites was 3.3 percent but was substantially lower at Category 3 sites (0.9 percent; Appendix Table A-6). This pattern of enriched organics in sediments at untreated sites and reduced organics at hydraulically treated sites is consistent with our paradigm of the effects of treatment; that is, it appears that the normal load of organic carbon at untreated sites is augmented with organic carbon from plants and animals killed by the oil, the oil itself, and bacteria that have colonized the sediments to exploit the oil as a rich source of carbon. In contrast, the hydraulic treatment flushes most of the normal load of organic carbon out of the sediments and replaces it with varying amounts of petroleum hydrocarbons.

Regarding the potential impact of bioaccumulated PAHs, Donkin et al. (1991) reported that "...many organic contaminants (specifically petroleum hydrocarbons) detected by chemical analysis of mussels have no direct effect on filter feeding, whereas the less frequently determined volatile compounds are toxic." Donkin et al. suggested that hydrocarbons occurring near their solubility limits in tissues may be sequestered in the tissues as crystalline material. Given that the 1992 PAH levels in mussel tissues from the several treatment categories are comparable to or less than levels in and near area population centers, and given the apparent robustness of mussel populations in such areas in south-central Alaska, there seems to be little likelihood of injury to mussels from these hydrocarbons.

CHAPTER 3

INTERTIDAL EPIBIOTA

INTRODUCTION

Epibiota data were collected in late June and early July 1992 at one or more elevations at 12 rocky, 12 mixed-soft, and 5 boulder/cobble sites. A summary of all 1990-92 intertidal and subtidal sampling tasks and months of collection is shown in Appendix Table A-1. Latitude and longitude coordinates from a global positioning system (GPS) for each of the study sites are found in Appendix Table A-2. Tidal elevations of stations at each study site are located in Appendix Table A-3.

Epibiota field sampling was conducted by intertidal ecologists with many years of experience in the taxonomy and natural history of Alaskan intertidal organisms. Some qualitative observations of trends or patterns observed in the course of field surveys are reported on the basis of this experience without quantitative measurements or without demonstration of statistical significance.

METHODS

Field

Water Quality

Water temperature and salinity were measured with a YSI 33 meter at 25 sites visited in June and July 1992 (Appendix Table A-4). The probe was gently lowered to about one foot and at some sites to seven to eight feet below the surface of the water, and water temperature (±1°C) and salinity (parts per thousand [ppt]) were read directly off the meter.

Tidal Elevations

Tidal elevations were calculated or observed empirically at all stations in 1992 (Appendix Table A-3). Readings for tidal elevations were made at at least two points along the transect line at each station using a surveyor's transit and stadia rod. The waterline was used as a reference point for determining the elevation of each station. The elevation of the waterline was calculated using a tidal reference software program, and elevation of each station was determined relative to the waterline.

Epibiota

The abundance of epibiota (plants and animals living on or attached to the substratum) was measured in June and July 1992 at two or three elevations on rock, boulder, and mixed-soft substrata (Table 1-1). Five to ten 0.25-m^2 quadrats were sampled on 30-m sampling lines (transects) oriented with the beach contour. Quadrats were repositioned at the same orientation previously sampled with the aid of rebar stakes, spikes, or epoxy markers placed in 1989, 1990, or 1991; where possible, the position of a quadrat was adjusted by referring to photographs taken during previous surveys.

Prior to sampling, each quadrat was photographed with a label showing the site, date, and quadrat number. Most taxa were identified by biologists in the field. Problematic taxa were collected (from outside the sample area, if possible) for cross-comparison among investigators or for identification on board the support vessel or in the laboratory. Biological variables measured or estimated included algal cover (percent by taxon) and numbers or percent cover of major epibenthic fauna. Relative cover estimates for biota, substratum types, and oiling were based on visual examination of the tops, sides, and overhangs within a quadrat, but rocks were not overturned. Visual estimation of percent cover by experienced biologists is more accurate and precise, especially for rare species, than 50- or 100-point contact methods (Dethier et al., 1992), and a combination of visual estimation with photographs has been found to be most effective for use in intertidal surveys (Meese and Tomich, 1992). Whenever any oil was found, a subjective description of oiling in each quadrat was recorded along with the percentage of oil cover found within the quadrat. Individual observers cross-checked each other at frequent intervals to ensure correct identification of biota and consistent estimation of percent cover.

Field Quality Assurance/Quality Control

All members of the field sampling team met and discussed procedures for field sampling at a mobilization meeting aboard each vessel before sampling to ensure that everyone understood the field methods to be used and that methods were followed consistently. This common understanding, along with the use of the same personnel, maximized consistency with procedures used in 1990 and 1991.

Several checks were made prior to any data collection in the field. Quadrats sampled at each location were checked against a master list of stations, dates of previous sampling, and quadrats that had previously been sampled destructively and nondestructively since 1989. This check precluded resampling an area previously sampled destructively. Notes on the orientation of the station line and any deviations in the previous samplings were also checked.

Some of the header information required on the data sheets (including location, elevation, date, and foot marker numbers of quadrats to be sampled) was filled out on board the support vessel prior to sampling. In mixed-soft habitats, where some quadrats had been destructively sampled, new quadrats were picked randomly from locations not previously sampled. Unique sample identification (ID) numbers were assigned before field sampling and recorded on electronic logsheets in a portable computer and on each data sheet, sampling bag, or jar. To create the numbers, the vessel prefix ("L" for one vessel and "N" for the other vessel) was followed by an eight-digit designation for the year, month, day, and sample number. Each vessel was assigned a block of numbers to serve as sample identification numbers, (i.e. samples from the *Arctic Dream* were assigned numbers from 01 to 50, and samples from the *Renown* were numbered from 51 to 99). This procedure helped ensure that duplicate numbers could not be assigned. The principal investigator checked these numbers against the computer logs to ensure that numbers were not duplicated. Members of the field team noted these numbers, and the type of sample to which each was assigned, in their field notebooks for reference in the field. Filling out the computer sample ID log prior to sampling ensured that all desired sampling activities were accomplished at each location.

On station, a GPS receiver was used to verify locations of sites and transects. Data sheets were checked to be sure header information was correct. The time sampling began was entered, and the data recorder checked quadrat numbers against the master station list to be sure that the quadrat numbers sampled were correct for the elevation. One person laid the tape in the appropriate direction from the station-origin stake and checked with the recorder to see if permanent quadrat locations lined up with markers. Deviations from previous samplings were noted on the data sheet. The initials of the recorder were placed at the top of the data sheet, and the initials of the quadrat enumerator were placed at the top of each data column.

There was frequent cross-checking of taxonomic identifications and estimates of percent cover between quadrat enumerators. Invertebrate nomenclature generally followed Kozloff (1987), and algal nomenclature followed Gabrielson et al. (1989). Problematic species and unique fauna and flora were placed in plastic bags, labeled, and returned to the support vessel for identification or for preservation as reference or voucher specimens. When sampling was finished, the recorder checked to make sure that all header information was entered on the data sheet, and another person checked that all information was complete. A final review of the data sheets was made later on board the support vessel and included checking of the sample ID numbers against those previously assigned. A duplicate sampling of six quadrats by a different pair of observers was also done at the Block Island middle rocky site (see Chapter 6). This sampling took place about one week after the initial sampling.

Statistical Analyses

Inferential Statistics

Various statistical analyses were applied to quantitatively describe the data (number of species, number of individuals, cover, species diversity, evenness) and evaluate the significance of the findings. Parametric and nonparametric tests were applied as appropriate to evaluate the significance of differences observed between station categories. In these tests the mean of all subsamples (replicates) at a given station was used to represent each variable; thus, n = the number of stations within that category where the variable in question was measured.

For tests of category effects and site-to-site differences in intertidal epibiota, infauna, and environmental variables, a critical value (alpha) of $p = 0.1$ was used. Eberhardt and Thomas (1991) note that the alpha of 0.05 "automatically" selected by most ecologists may be inappropriate in some cases. Use of 0.1 allows that there is a one-in-ten chance of falsely rejecting the null hypothesis ("no difference between site categories"—Type I error). If there is a greater concern for falsely accepting a null hypothesis that is in fact false (i.e., failure to identify significant effects of oiling or treatment when they exist—Type II error), then a lower critical value may be justified.

Eberhardt and Thomas (1991) note further that a disparity commonly occurs about probability values between analysts on opposing sides of a controversial environmental issue. Those wishing to show "no effect" may ignore a Type II error and opt for a critical p value of 0.05 or even 0.01; those concerned with not missing an impact choose a higher probability value to reduce the Type II error. Therefore, the authors have considered probability levels of 0.1 or less to represent significant differences (i.e., to reject the null hypothesis) in most aspects of this study. Use of the randomization approach to ANOVA and t-testing (see below) allows computation of exact p values, which are provided in the text and on tables.

Many trends are noted as differences in mean values where no probability value is given. These differences are considered biologically relevant even though they are not statistically significant, often because of the limited replication of stations within site categories. Differences described between site categories also have been tested between pairs of stations representing those categories, often with significant results because of the greater sample size available.

Randomization Tests

Enumeration data were first tested for significant category effects (see null hypotheses in Chapter 1) using a randomization ANOVA and then tested for significant differences between pairs of site categories with a 2-tailed randomization t-test (Edgington, 1987).

Randomization tests are distribution-free statistical tests in which the data are repeatedly reassigned among and between treatment groups. First, a test statistic (e.g., t or F statistic) is computed for the initial data set. The data set is then randomly shuffled and the test statistic recalculated. Following a thousand or more passes of this iterative process, the proportion of random test statistics greater than or equal to the initial test value represents the exact significance of the results. All assumptions of normality, homogeneity of variance, and other characteristics of randomly sampled populations are unnecessary, with one exception: that the data set truly represents the population of interest (i.e., is sampled randomly; Edgington, 1987):

> "Randomization tests, when conventional test statistics are computed, are not alternatives to the conventional tests; rather they are those [same] tests with the significance determined by a special procedure."

Randomization ANOVA tests performed on epibiota (middle rocky stations) data collected in 1990 indicated that, for certain dominant taxa, there were significant category effects—that is, abundance varied significantly among treatment categories. Multiple comparison tests using the 1990 data (Houghton et al., 1991a) identified significant ($p < 0.1$) differences in abundances of certain taxa between various permutation pairs of site categories. The same approach, ANOVA for category effects followed by t-tests for significance of differences between pairs of site categories, was applied in 1991 and 1992. Because a main purpose of this study is to assess the degree of recovery occurring over time, it was considered important to continue to test for differences between pairs of site categories, even for taxa for which no experiment-wise category effect remained in 1991 or 1992. It is recognized that such multiple comparisons have a statistical penalty in the true experiment-wise alpha (Type I error term): differences calculated to have an alpha of 0.1 in the multiple comparison randomization t-tests in fact represent differences that have a greater than one-in-ten chance of occurring randomly.

For epibiota, detailed abundance data (Appendix C) were used in calculations of total algal cover and total taxa present. Certain taxa were subsequently combined into higher taxonomic groups (e.g., all species of limpets into the family Lottiidae) for ease of presentation (e.g., Tables 3-1 through 3-9) and for statistical testing. A randomization ANOVA was used to determine if a significant category effect existed and was followed by randomization t-tests for differences among station categories for dominant taxonomic groups.

Table 3-1 Mean abundance (% or no./0.25 square m) of important epibiota at upper rocky sites, July 1992. (*$p \leq 0.10$; **$p < 0.05$).

Category	1		2		3		Randomization	Randomization t-tests		
Lumped taxon	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**ANOVA**	**1 vs. 2**	**1 vs. 3**	**2 vs. 3**
Plants (% cover)										
Encrusting Phaeophyta	0.00	0.00	0.00	0.00	1.47	1.52	**		*	*
Encrusting Rhodophyta	0.93	1.45	1.03	1.54	1.00	1.39				
Endocladiaceae	1.07	1.76	1.60	2.12	0.10	0.17				
Filamentous Chlorophyta	0.00	0.00	0.00	0.00	0.53	0.92				
Fucus gardneri	1.53	1.91	6.53	7.82	2.17	2.06				
Fucus gardneri (sporeling)	0.57	0.35	0.40	0.35	0.20	0.20				
Verrucaria spp.	26.40	40.64	1.60	2.60	8.37	8.72				
Total plant cover (%)	**30.77**		**11.37**		**14.57**					
Number of plant taxa ◊	**5.3**		**4.7**		**7.0**					
Animals (% cover or no./0.25 square m)										
Balanus glandula (%)	0.27	0.06	0.00	0.58	0.54	0.42		*		
Chthamalus dalli (%)	1.77	2.55	0.40	0.44	0.37	0.21				
Ligia sp. (#)	0.93	1.45	0.47	0.81	0.07	0.12				
Littorina scutulata (#)	62.47	32.31	88.80	87.01	148.87	88.57				
Littorina sitkana (#)	62.40	68.17	41.00	26.72	99.60	117.48				
Lottiidae (#)	28.60	46.27	2.20	0.53	1.73	0.95				
Musculus spp. (#)	1.20	2.08	0.00	0.00	0.00	0.00				
Mytilus edulis (%)	0.30	0.26	0.17	0.29	0.10	0.00				
Nucella lamellosa (#)	1.13	1.96	0.07	0.12	0.00	0.00				
Semibalanus balanoides (%)	6.90	11.69	0.70	0.44	0.97	1.50				
Number of animal taxa ◊	**10.0**		**7.3**		**8.3**					
Other (% cover or no./0.25 square m)										
Boulder/cobble (%)	6.67	11.55	41.07	47.71	18.87	32.68				
Gravel/sand (%)	0.00	0.00	1.47	2.54	1.17	1.93				
Oil cover (primary) (%)	0.03	0.06	0.50	0.56	0.27	0.23				
Oil scale (primary) (#)	0.40	0.69	3.60	3.17	3.20	2.77				
Rock (%)	93.33	11.55	57.47	50.23	80.00	34.64				
Water (%)	0.00	0.00	0.00	0.00	1.33	2.31				
Number of stations	3		3		3					

◊ Mean number of taxa per station within each category; see detailed data in Appendix C.

Table 3-2 Mean abundance (% or no./0.25 square m) of important epibiota at middle rocky sites, July 1992 (*p < 0.10; **p < 0.05).

Category	1		2		3		Randomization	Randomization t-tests		
Lumped taxon	Mean	SD	Mean	SD	Mean	SD	ANOVA	1 vs. 2	1 vs. 3	2 vs. 3
Plants (% cover)										
Elachista fucicola	1.18	2.05	0.25	0.43	0.00	0.00				
Encrusting Phaeophyta	0.15	0.13	0.43	0.50	0.63	0.81	*		*	*
Encrusting Rhodophyta	3.20	5.20	1.38	1.43	0.60	0.71				
Endocladiaceae	1.68	0.63	2.25	1.88	2.43	3.08	*		*	
Filamentous Chlorophyta	0.90	0.75	1.93	2.74	0.30	0.28				
Filamentous Phaeophyta	0.37	0.40	5.77	4.33	0.40	0.57				
Fucus gardneri	38.47	9.25	51.30	30.01	43.60	27.44				
Fucus gardneri (sporeling)	0.68	0.03	0.55	0.31	0.13	0.11				
Gigartinaceae	0.37	0.64	0.67	1.07	0.00	0.00				
Halosaccion glandiforme	0.12	0.20	0.57	0.98	0.00	0.00				
Rhodomeleae/Cryptosiphonia spp.	0.40	0.44	1.52	1.77	1.50	1.27				
Total plant cover (%)	**49.67**		**67.88**		**49.95**					
Number of plant taxa ◊	**13.3**		**20.3**		**17.7**					
Animals (% cover or no./0.25 square m)										
Balanus glandula (%)	3.63	5.15	0.37	0.28	0.55	0.35				*
Chthamalus dalli (%)	3.40	2.98	8.87	14.23	6.68	8.38				
Littorina scutulata (#)	54.67	56.68	83.63	92.58	360.00	104.09				
Littorina sitkana (#)	91.63	67.63	79.17	73.57	68.00	22.34				
Lottiidae (#)	22.30	10.39	16.53	4.40	26.90	11.46				
Lottiidae (juv.) (#)	6.27	5.00	13.57	8.23	6.05	1.63				
Mytilus edulis (%)	4.15	4.58	3.40	2.78	1.23	1.73				
Mytilidae, (spat) (%)	3.07	4.28	0.40	0.36	0.53	0.53				
Nucella lamellosa (#)	3.67	6.18	1.00	1.73	7.30	10.32				
Pagurus hirsutiusculus (#)	11.87	9.00	5.13	3.87	2.50	0.42	**	**	*	
Semibalanus balanoides (%)	3.28	4.06	4.30	5.38	12.88	2.09				
Semibalanus cariosus (%)	5.50	9.48	0.00	0.00	0.00	0.00				
Siphonaria thersites (#)	1.40	1.31	4.43	7.68	1.65	2.19				
Number of animal taxa ◊	**19.3**		**19.7**		**15.8**					
Dead organisms (% cover or no./0.25 square m)										
Mytilus edulis (dead) (#)	7.07	7.45	1.30	1.14	0.40	0.57				
Semibalanus balanoides (dead) (%)	0.70	0.61	2.20	3.12	0.75	0.92				
Other (% cover)										
Boulder/cobble	52.40	19.75	57.77	47.48	3.20	4.53				
Gravel/sand	7.97	9.39	2.00	2.65	0.50	0.71				
Rock	39.63	28.16	39.97	48.48	94.90	7.21				
Water	0.23	0.32	0.03	0.06	2.30	1.56				
Number of stations	3		3		3					

◊ Mean number of taxa per station within each category; see detailed data in Appendix C.

Table 3-3. Mean abundance (% or no./0.25 square m) of important epibiota at lower rocky sites, July 1992. (*p < 0.10; **p < 0.05; ***p < 0.01).

	1		2		3		Randomization	Randomization	
Lumped taxon	Mean	SD	Mean	SD	Mean	SD	ANOVA	1 vs. 2	1 vs. 3
Plants (% cover)									
Articulated coralline algae	0.15	0.15	2.13	3.01	0.06				
Delesseriaceae	1.52	1.06	4.59	6.50	0.00				
Encrusting Phaeophyta	0.62	0.78	0.23	0.24	5.94				
Encrusting Rhodophyta	1.52	2.00	0.18	0.25	0.83				
Filamentous Chlorophyta	17.77	10.68	35.55	23.41	2.17				
Filamentous Phaeophyta	5.53	5.19	14.42	19.77	0.33				
Filamentous Rhodophyta	4.47	4.76	4.59	2.88	0.06				
Foliose green algae	10.57	10.08	6.88	2.93	1.72				
Fucus gardneri	41.60	17.00	19.74	16.78	59.56				
Gigartinaceae	6.62	2.56	2.93	3.29	1.22				
Halosaccion glandiforme	6.90	4.94	0.28	0.32	0.50				
Palmaria spp.	3.93	5.17	4.94	6.36	0.11				
Rhodomeleae/Cryptosiphonia spp.	10.85	5.67	27.49	4.68	5.94		*		*
Total plant cover (%)	**116.48**		**127.64**		**82.17**				
Number of plant taxa ◊	**33.30**		**29.00**		**28.00**				
Animals (% cover or no./0.25square m)									
Chthamalus dalli (%)	1.15	1.49	0.18	0.17	0.50				
Encrusting bryozoan (%)	5.22	5.50	0.70	0.42	0.11				
Lacuna spp. (#)	4.80	6.45	0.79	0.58	1.00				
Littorina scutulata (#)	2.20	3.39	1.31	1.68	58.11				
Littorina sitkana (#)	0.93	1.62	0.50	0.71	1.44				
Lottiidae (#)	3.87	6.44	3.28	4.28	0.44				
Lottiidae (juv.) (#)	8.83	5.76	5.95	8.41	143.89		*		*
Margarites spp. (#)	3.37	3.71	0.00	0.00	0.00				
Mytilidae, (spat) (%)	5.00	1.34	0.77	0.11	0.72		*		*
Nucella lamellosa (#)	16.67	17.95	1.84	2.17	0.00				
Nucella spp. (#)	7.23	12.53	0.15	0.21	0.00				
Pagurus hirsutiusculus (#)	3.60	3.95	6.23	8.45	23.56				
Semibalanus balanoides (%)	0.02	0.03	1.03	1.45	0.06				
Semibalanus cariosus (%)	10.35	17.88	0.00	0.00	0.00				
Spirorbidae (%)	1.17	0.98	0.34	0.49	0.72				
Number of animal taxa ◊	**23.30**		**17.00**		**21.00**				
Dead organisms (no./0.25 square m)									
Mytilus edulis (dead) (#)	4.42	2.65	1.30	0.42	0.72				
Other (% cover)									
Boulder/cobble	15.37	14.63	98.10	2.69	0.67		**	*	**
Gravel/sand	3.43	4.40	1.90	2.69	1.89				
Rock	81.20	18.99	0.00	0.00	97.44		**	*	**
Number of stations	3		2		1				

◊ Mean number of taxa per station within each category; see detailed data in Appendix C.

Table 3-4. Mean abundance (% or no./0.25m^2) of important epibiota at upper boulder/cobble intertidal sites, July 1992.

Category Taxon	1	3
	Mean	Mean
Plants (% cover)		
Endociadiaceae	0.00	0.29
Fucus gardneri (sporeling)	0.00	0.14
Chlorophyta	0.25	0.07
Total plant cover (%)	**0.25**	**0.50**
Number of plant taxa*	**1.00**	**3.00**
Animals (% cover or no. 0.25 m^2)		
Balanus glandula (%)	2.15	0.36
Chthamalus dalli (%)	0.75	1.21
Littorina scutulata (#)	4.70	24.14
Littorina sitkana (#)	12.40	31.00
Littorina spp. (juv) (#)	0.10	5.14
Lottiidae (#)	9.50	6.29
Mytilus edulis (#)	2.00	0.14
Semibalanus balancides (%)	1.90	0.26
Number of animal taxa*	**9.00**	**11.00**
Other (% cover or no./0.25m^2)	95.60	99.57
Boulder/cobble (%)	95.60	99.57
Gravel/sand (%)	4.40	0.43
Oil cover (primary (%)	0.00	0.07
Oil scale (primary (%)	0.00	0.86
Number of stations	1	1

*Mean number of taxa per station within each category; see detailed data in Appendix C.

Table 3-5. Mean abundance (% or no./0.25m^2) of important epibiota at upper boulder/cobble intertidal sites, July 1992.

Category Taxon	3 Mean	 SD
Plants (% cover)		
Encrusting *Phaeophyta*	0.36	0.73
Encrusting *Rhodophyta*	2.09	3.95
Endocladiaceae	0.51	33.98
Total plant cover (%)	20.45	
Number of plant taxa*	2.50	
Animals (% cover or no./0.25m^2)		
Chthamalus dalli (%)	0.63	0.25
Littorina scutulata (#)	20.30	16.07
Littorina sitkana (#)	193.80	154.42
Littorina spp. (juv) (#)	39.83	49.21
Littiidae (#)	8.48	3.46
Lottiidae (juv) (#)	9.55	13.01
Mytilus edulis)%)	1.21	1.58
Pagurus hirsutiusculus (#)	4.73	9.45
Semibalanus balanoides (%)	6.38	11.11
Number of animal taxa*	**11.70**	
Other (% cover or #)		
Boulder/cobble (%)	96.15	2.46
Gravel/sand (%)	2.10	1.89
oil cover (primary) (%)	0.04	0.05
Oil scale (primary) (#)	0.45	0.57
Rock (%)	1.75	3.50
Water (%)	2.13`	1.85
Number of stations	4	

*Mean number of taxa per station within each category; see detailed data in Appendix C.

Table 3-6. Mean abundance (% or no./0.25m^2) of important epibiota at upper boulder/cobble intertidal sites, July 1992.

Category	3	
Taxon	Mean	SD
Encrusting *Phaeophyta*	8.68	0.25
Enteromorpha spp.	4.90	3.89
Filamentous Chlorophyta	2.35	1.91
Pilamentous Phaeophyta	4.23	3.71
Foliose green algae	1.83	1.52
Fucus gardneri	0.38	0.32
Laminaria spp.	1.35	1.91
Miscellanous Phaeophyta	7.40	9.83
Total plant cover (%)	**37.33**	
Number of plant taxa*	**23.50**	
Animals (% cover or no./0.25 m^2)		
Littorina sitkana (#)	1.70	2.40
Littiidae (#)	8.75	12.23
Musculus spp. (#)	1.25	1.77
Spirorbidae ($)	2.13	2.51
Number of animal taxa*	**14.00**	
Other (% cover)		
Boulder/cobble	97.95	2.76
Gravel/sand	**2.08**	2.79
Number of stations	2	

Table 3-7 Mean abundance (% or no./0.25 square m) of important epibiota at upper mixed soft sites, July 1992 (*p < 0.10).

Category	1		2		3		Randomization	Randomization t-tests		
Lumped Taxon	Mean	SD	Mean	SD	Mean	SD	ANOVA	1 vs. 2	1 vs. 3	2 vs. 3
Plants (% cover)										
Fucus gardneri	1.70	2.94	0.80	1.13	0.00	0.00				
Fucus gardneri (sporeling)	0.07	0.06	0.10	0.14	0.20	0.00			*	
Vascular plants	3.47	6.00	31.00	43.84	0.00	0.00				
Total plant cover (%)	**5.47**		**32.15**		**0.35**					
Number of plant taxa ◊	**3.3**		**4.0**		**2.0**					
Animals (% cover or no./0.25 square m)										
Littorina scutulata (#)	48.60	74.03	53.40	74.95	29.10	40.31				
Littorina sitkana (#)	12.93	8.20	21.30	17.68	100.30	135.34				
Lottiidae (#)	0.67	0.31	1.10	1.27	1.10	1.56				
Lottiidae (juv.) (#)	0.00	0.00	0.00	0.00	2.80	3.96				
Semibalanus balanoides (%)	1.27	1.59	0.55	0.07	2.85	3.75				
Number of animal taxa ◊	**8.7**		**6.0**		**8.5**					
Dead organisms (% cover)										
Semibalanus balanoides (dead) (%)	0.10	0.17	0.15	0.07	0.10	0.14				
Other (% cover or no./0.25 square m)										
Boulder/cobble (%)	30.27	26.00	48.80	12.45	42.80	60.53				
Gravel/sand (%)	69.73	26.00	51.20	12.45	57.20	60.53				
Oil cover (primary) (%)	0.00	0.00	2.05	2.90	0.00	0.00				
Oil scale (primary) (#)	0.00	0.00	1.20	1.70	0.00	0.00				
Number of stations	3		2		2					

◊ Mean number of taxa per station within each category; see detailed data in Appendix C.

Table 3-8 Mean abundance (% or no./0.25 square m) of important epibiota at middle mixed soft sites, July 1992. (*p < 0.10; **p < 0.05; ***p < 0.01).

Category	1		2		3		Randomization	Randomization t-tests		
Lumped taxon	Mean	SD	Mean	SD	Mean	SD	ANOVA	1 vs. 2	1 vs. 3	2 vs. 3
Plants (% cover)										
Elachista spp.	0.00	0.00	2.20	3.11	0.00	0.00				
Enteromorpha spp.	0.07	0.12	0.50	0.71	0.00	0.00				
Filamentous Chlorophyta	0.46	0.15	0.18	0.25	0.00	0.00	*		*	
Fucus gardneri	4.88	4.11	50.35	38.68	4.91	5.44	**	*		*
Fucus gardneri (sporeling)	0.12	0.11	0.45	0.42	0.10	0.20				
Total plant cover (%)	**8.02**		**54.55**		**6.20**		***	*		*
Number of plant taxa ◊	**7.3**		**10.0**		**3.2**				*	*
Animals (% cover or no./0.25 square m)										
Balanus glandula (%)	0.65	0.77	0.15	0.21	1.04	1.14				
Littorina scutulata (#)	175.72	176.05	50.25	68.66	169.35	176.80				
Littorina sitkana (#)	47.24	40.84	58.00	82.02	178.88	146.30				
Lottiidae (#)	5.31	4.46	3.05	4.03	6.38	4.01				
Lottiidae (juv.) (#)	12.12	12.61	82.40	116.53	2.80	2.33				
Mytilus edulis (%)	11.98	10.16	44.60	42.14	3.23	2.41	**		**	*
Pagurus hirsutiusculus (#)	0.37	0.55	1.75	2.33	0.88	0.94				
Semibalanus balanoides (%)	8.63	7.16	2.80	3.96	1.68	1.09				
Number of animal taxa ◊	**10.3**		**11.5**		**11.7**					
Dead organisms (% cover or no./0.25 square m)										
Mytilus edulis (dead) (#)	3.74	2.48	12.75	15.49	1.85	2.30				*
Other (% cover)										
Boulder/cobble	43.94	37.58	11.75	8.27	39.25	32.29				
Gravel/sand	56.06	37.58	85.25	4.03	60.38	32.84				
Mud	0.00	0.00	3.00	4.24	0.00	0.00				
Rock	0.00	0.00	0.00	0.00	0.38	0.75				
Water	1.10	1.28	0.00	0.00	0.03	0.05				
Number of stations		3		2		4				

◊ Mean number of taxa per station within each category; see detailed data in Appendix C.

Table 3-9. Mean abundance (% or no./0.25 square m) of important epibiota at lower mixed soft sites, July 1992 (*p < 0.10; **p < 0.05).

Category	1		2		3		Randomization	Randomization t-tests		
Lumped taxon	Mean	SD	Mean	SD	Mean	SD	ANOVA	1 vs. 2	1 vs. 3	2 vs. 3
Plants (% cover)										
Encrusting Phaeophyta	0.17	0.29	0.69	1.02	1.37	2.37				
Enteromorpha spp.	5.17	8.78	1.72	2.15	0.15	0.18				
Filamentous Chlorophyta	17.28	24.17	28.09	36.12	0.73	0.53				
Filamentous Phaeophyta	1.42	1.30	14.23	21.05	1.32	1.15				
Filamentous Rhodophyta	1.22	1.68	0.63	0.84	0.02	0.03			**	
Foliose green algae	1.22	1.28	2.93	4.33	1.10	1.05				
Fucus gardneri	8.62	11.18	9.92	10.52	2.90	1.92				
Misc. Phaeophyta	0.18	0.16	0.09	0.11	0.45	0.49				*
Palmaria spp.	0.02	0.03	0.18	0.27	1.92	3.32				
Rhodomeleae/Cryptosiphonia spp.	7.32	9.80	4.73	9.33	3.67	3.22				
Total plant cover (%)	**43.87**		**65.00**		**15.47**					
Number of plant taxa ◊	**15.3**		**15.0**		**17.7**					
Animals (% cover or no./0.25square m)										
Gnorimosphaeroma oregonensis (#)	0.00	0.00	0.46	0.97	0.23	0.12			*	
Lacuna spp. (#)	1.03	1.45	25.92	55.42	0.03	0.06			*	
Leptasterias spp. (#)	0.13	0.23	0.40	0.21	0.03	0.06	*			**
Littorina scutulata (#)	135.07	122.17	9.88	12.26	280.80	351.02				**
Littorina sitkana (#)	19.27	32.34	10.80	18.18	45.23	63.93				
Lottiidae (#)	4.57	3.40	4.42	6.87	3.97	0.42				
Lottiidae (juv.) (#)	24.03	27.55	20.30	28.07	28.70	39.62				
Mytilus edulis (%)	2.85	2.27	1.46	2.13	3.07	3.67				
Mytilidae, (spat) (%)	0.93	1.10	1.51	2.60	1.23	0.64				
Nemertea (#)	0.20	0.10	0.02	0.04	0.10	0.17	*	**		
Nucella lima (#)	0.67	0.81	0.48	0.96	0.00	0.00			*	
Pagurus hirsutiusculus(#)	1.00	0.52	5.32	8.18	1.40	0.66				
Semibalanus balanoides (%)	0.15	0.09	0.12	0.06	0.63	0.74	*			
Number of animal taxa ◊	**21.3**		**21.2**		**17.0**					

◊ Mean number of taxa per station within each category; see detailed data in Appendix C.

Table 3-9 (continued)

Category	1		2		3		Randomization	Randomization t-tests		
Lumped taxon	Mean	SD	Mean	SD	Mean	SD	ANOVA	1 vs. 2	1 vs. 3	2 vs. 3
Dead organisms (no./0.25 square m)										
Mytilus edulis (dead)	1.37	1.34	2.38	2.02	4.50	5.60				
Other (% cover or no./0.25 square m)										
Boulder/cobble (%)	27.20	17.80	28.78	20.53	46.50	23.26				
Gravel/sand (%)	64.27	13.48	71.22	20.53	53.63	23.13				
Mud (%)	5.87	9.48	0.00	0.00	0.00	0.00				
Otter feeding pits (#)	0.00	0.00	1.40	3.13	0.00	0.00				
Water (%)	2.67	4.62	12.76	23.11	9.23	15.99				
Number of stations	3		4		3					

Multivariate Analysis

The species abundance data set was also examined using nonmetric multidimensional scaling (NMDS), a multivariate ordination technique. NMDS works roughly like principal components analysis (PCA) except instead of analyzing the variance of species abundance, NMDS first converts the data set to a matrix of similarity coefficients by comparing each site to all other sites and to a matrix of Euclidean distances from the original species abundance values. The analysis then proceeds to rank and adjust the location of each site in similarity space until an optimal fit between the two matrices is obtained, axes fitted, and component scores calculated. During the adjustment in similarity space, the analysis automatically attempts to linearize the gradient for each axis; thus the analysis is scaled and results in a derivative representation of the original similarity space. Goodness of fit is measured by a "stress" value that represents the departure from monotonicity and can further be used to judge the optimal number of the components to use in the final analysis.

As in any other multivariate techniques, species rare in abundance or distribution are removed from the initial analysis to reduce the noise in the system. The remaining abundances then are log transformed to reduce population-scaling effects. Polyspecific groups are usually discarded to avoid distorting the discrimination between sites.

The resulting component scores are plotted on three-dimensional axes and examined for significant site clustering, for indications of site similarities, and for movement between years for indications of trends in successional recovery. Sites with single-event samplings were evaluated by their proximity to neighboring sites. Unfortunately, the ranking and scaling involved in the NMDS procedure and the mixed metric nature of the data preclude most post-hoc examinations to determine the most important parameters behind the patterns. Nonparametric rank correlation (Spearman's rho), however, was used to investigate the relationship of the X-axis scores with species richness.

Validation of the results was confirmed using detrended reciprocal averaging (DRA), another multivariate ordination technique. Typically, the data sets were log transformed, and the Bray-Curtis index was used for the similarity calculations. Rare species were dropped and outlier stations deleted before the final analyses. The data matrices were initially run through a principal coordinates analysis (PCORD), a metric version of NMDS, both to obtain a trial vector matrix needed for NMDS and to preevaluate the best dimensionality of the final components. The BIOSTAT II computer package (Pimentel and Smith, 1986) was used for all multivariate analyses.

For each of the multivariate techniques, determining which component axes were significant contributors to the final ordination was based on the SCREE diagram technique. With this technique the percent variance accounted for by each axis is plotted as a simple line graph. The axis at which the line first breaks or begins to plateau is considered the least significant axis to include in the interpretation. Typically, no more than two or three axes were significant throughout this study.

RESULTS

Physical Measurements

Water temperature and salinity were measured at 28 sites from 23 locations. Lowest water temperature (7.8°C) was recorded at Bainbridge Bight, and highest water temperature (18°C) was measured at Bass Harbor (Appendix Table A-4). The lowest salinity (6.8 ppt) was recorded at Bainbridge Bight; the highest salinity (28 ppt) was found at Smith Island.

Rocky Habitats

Twelve rocky sites were sampled at one or more elevations in June and July 1992 (see Table 1-1). Mean abundances of important epibiota at rocky habitats are shown in Tables 3-1, 3-2, and 3-3; abundances of dominant taxa are displayed in Figure 3-1. Detailed data on taxon abundances by individual station are provided in Appendix Tables C-1-1 to C-1-3. A randomization ANOVA performed on the dominant epibiota at middle elevation stations in 1992 found few significant category effects on the assemblage "dominants." Because a main purpose of this study is to assess the degree of recovery occurring over time, it was considered important to continue to test for differences between site categories, even for taxa for which no category effect remained in 1991 or 1992. Because this approach involves multiple comparisons using the same data, p values of 0.1 or less from randomization t-tests are provided with recognition that these values do not represent the true experiment-wise alpha.

Upper Stations

Although only one significant category effect (encrusting Phaeophyta; $p < 0.05$) was found among the epibiota in an ANOVA, general trends of some of the important biota at upper rocky stations are presented for comparison with results from other elevations.

At upper rocky stations *Fucus* was found at low abundances throughout all categories (Figure-3-1); Category 2 stations had a mean abundance of about 6.5 percent, and Category 1 and Category 3 stations averaged 1.5 to 2 percent. Total plant cover and mean number of plant taxa were low for all category sites (Table 3-1). Both littorine snail species (*Littorina sitkana* and *L. scutulata*) were most abundant at Category 3 stations (Figure 3-1), but these differences were not statistically significant. The barnacle *Semibalanus balanoides* mainly occurred at Category 1 upper stations (Table 3-1). *Balanus glandula* was significantly more abundant at Category 1 sites than at Category 2 sites ($p < 0.10$; randomization t-test).

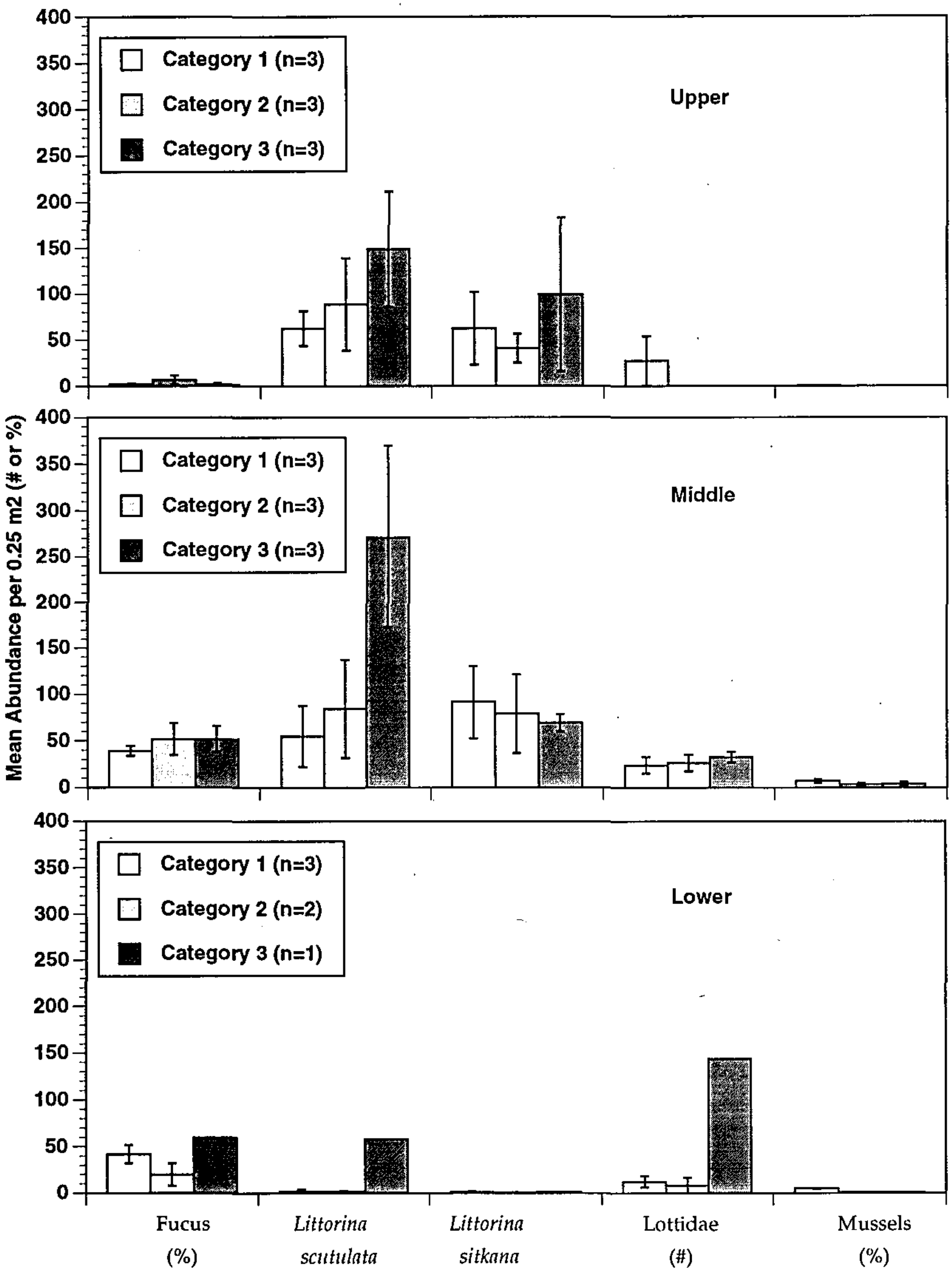

Figure 3-1. Mean abundance (± 1 SE) of major epibiota taxa at rocky sites, July 1992.

Middle Stations

Mean percent cover of *Fucus* at middle elevations in 1992 was nearly equal across all categories; mean abundance was lowest at Category 1 sites (Figure 3-1). The Endocladiaceae and encrusting browns were the only algal taxa that were significantly different among categories in an ANOVA ($p < 0.10$; Table 3-2). Both lumped taxa were significantly higher at the Category 3 middle stations than at the Category 1 stations in t-tests ($p < 0.10$). Only encrusting browns were significantly higher in a t-test at Category 3 stations than at Category 2 stations ($p < 0.10$).

The hermit crab *Pagurus hirsutiusculus* was the only animal taxon that was significantly different among categories ($p < 0.05$; ANOVA). Category 1 had significantly more hermit crabs than either Category 2 or Category 3 ($p < 0.05$ and $p < 0.10$, respectively; randomization t-tests).

Numbers of the snail *L. scutulata* were highest at the Category 3 stations (Figure 3-1). The Northwest Bay West Arm and the Northwest Bay Rocky Islet Category 3 sites had especially large numbers of *L. scutulata* (433 and 286 individuals/0.25 m^2, respectively; Appendix Table C-1-2). In contrast, *L. sitkana* abundance was highest at Category 1 stations (Table 3-2).

Adult limpets (Lottiidae) were found at essentially equal abundances across all categories (Figure 3-1 and Table 3-2), although more juveniles were counted at the Category 2 middle stations (Table 3-2).

Lower Stations

At lower rocky stations only the Rhodomeleae/*Cryptosiphonia* spp. complex was significantly different among site categories in an ANOVA ($p < 0.10$). *Fucus* cover was lowest at Category 2 sites (19.7 percent), but these sites had the highest cover of filamentous green and brown algae and of the Rhodomeleae/*Cryptosiphonia* spp. complex (Table 3-3). The one lower elevation Category 3 station at Northwest Bay Rocky Islet had a higher cover of *Fucus* than either Category 1 or Category 2 lower stations (Appendix C-1-3; Table 3-3; Figure 3-1).

Juvenile limpets (Lottiidae) and mussel spat were both significantly different among categories ($p < 0.10$; ANOVA); juvenile limpet abundances were highest at Category 3 sites, and mussel spat was highest at Category 1 sites. The Northwest Bay Rocky Islet lower station had high numbers of *Littorina scutulata* and Lottiidae; most of the limpets were juvenile animals (Appendix Table C-1-3; Figure 3-1).

Boulder/Cobble Habitats

Five boulder/cobble sites were sampled at one or more elevations in June and July 1992 (Table 1-1). Because of low replication of stations within each site category, only qualitative comparisons among mean abundances are possible for this habitat type. Detailed species abundance data are presented in Appendix Tables C-2-1 to C-2-3. Boulder/cobble habitats reflect conditions of high wave energy where movement of the substratum during winter storms limits the development of perennial biota. Upper elevations in particular showed only limited attached biota apart from barnacles and mussels (Table 3-4). In some areas (e.g., Northeast Latouche and Point Helen N3) smaller boulders that are unstable in winter storms overlie larger, generally stable boulders. In such environments mussels were sometimes found deep in protected crevices of the middle elevations.

Upper Stations

At upper intertidal stations on boulder/cobble habitats, there were virtually no macroalgae. Total percent plant cover was only 0.25 percent and 0.50 percent at the Category 1 and Category 3 sites, respectively (Table 3-4). Attached fauna were also sparse and were composed primarily of *Balanus glandula*, *Semibalanus balanoides*, and mussels (mean of 2.15, 1.90, and 2.00 percent cover at the Category 1 Bass Harbor site) and *Chthamalus dalli* (1.21 percent cover at the Category 3 Point Helen N3 site; Table 3-4). Motile grazers were common at both site categories. Both littorine species and juvenile limpets were more abundant at the Category 3 site; adult limpets were more abundant at the control site.

Middle Stations

Algae were also depauperate at the middle elevation in boulder/cobble habitats; *Fucus* and an encrusting red, probably *Petrocelis*, were the primary species present (Table 3-5). The Omni-barge test site (just outside Herring Bay; atypical of the other boulder/cobble sites) had the highest *Fucus* cover by a substantial amount (68 percent); the other three sites had either a trace or no *Fucus* at all (Appendix Table C-2-2). Littorines of both species were more abundant than at upper elevations, especially *L. sitkana* at the Omni-barge site and at Northeast Latouche (Appendix Table C-2-2; Figure 3-2). Juvenile limpets were abundant at the Point Helen N3 site with 28.3/0.25 m^2; hermit crabs were found only at the Omni-barge site (Appendix Table C-2-2).

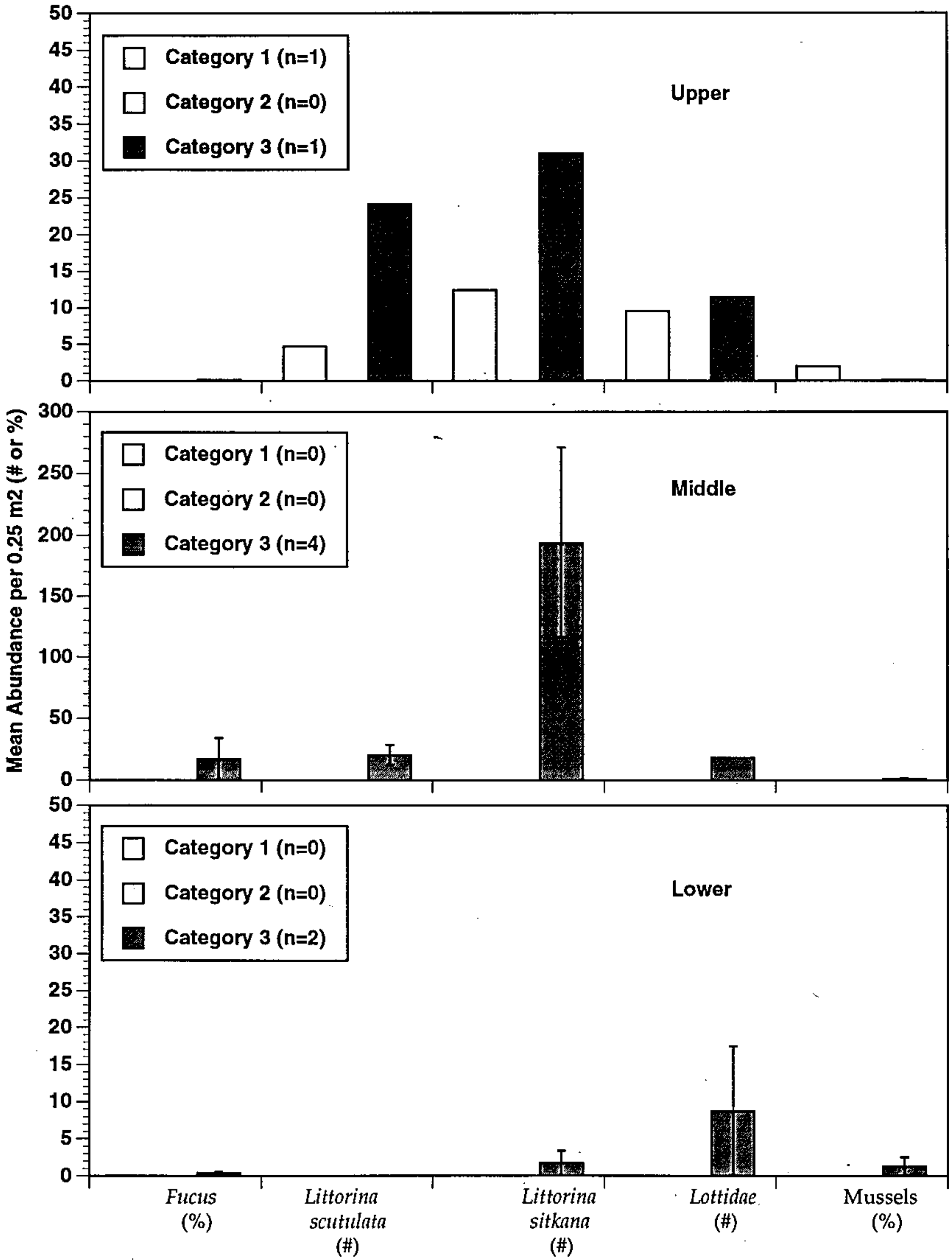

Figure 3-2 Mean Abundance (± 1 SE) of major epibiota taxa at boulder/cobble sites, July 1992. Note change of scale in middle chart.

Lower Stations

The two lightly oiled Category 3 lower boulder/cobble stations sampled (Point Helen N3 and Northeast Latouche) had more algal species present than the middle or upper elevations, although no species was dominant. Total plant cover was 37.3 percent (Table 3-6), substantially more than at the upper or middle elevations. No animals were found in high numbers except for limpets at Northeast Latouche. Because Point Helen and Northeast Latouche are highly exposed to storms and large waves, it was expected that attached epibiota abundances would be low.

Mixed-Soft Habitats

The 12 mixed-soft sites sampled in June and July 1992 represented a wide range of physical conditions (substratum, slope, exposure, oiling, and treatment) (Table 1-1; detailed species abundance data in Appendix Tables C-3-1 to C-3-3). Additional lower stations were added in 1992 at Crab Bay (Category 1) and Elrington Island West (Category 3). The old Crab Bay lower station sampled in 1990 was not resampled in 1992 because its substratum was predominantly sand; the new site consisted mainly of a gravel-cobble-silt mixture more similar to the substrata at other mixed-soft sites.

Upper Stations

At the upper mixed-soft stations epibiota was very sparse. No significant differences were found among plant or animal taxa in a randomized ANOVA, but Category 3 sites had a higher abundance of *Fucus* sporelings when compared to Category 1 sites in a t-test ($p < 0.10$; Table 3-7). Fauna was dominated by the two species of littorines (Table 3-7 and Figure 3-3). *Littorina sitkana* was most abundant at the Category 3 stations, mainly because of the high numbers of smaller individuals found at Sleepy Bay (Appendix Table C-3-1).

Middle Stations

At the middle mixed-soft stations, significant category effects were found in abundance of filamentous green algae, *Fucus*, total plant cover, and mussels (Table 3-8) ($p < 0.10$; < 0.05; < 0.001; < 0.05 respectively; randomization ANOVA). The Category 2 stations had significantly higher abundances of *Fucus* than did Category 1 or Category 3 stations (all $p < 0.10$; randomization t-tests). Category 1 stations had significantly higher numbers of plant taxa ($p < 0.10$; randomization t-test) and *Mytilus* ($p < 0.05$) than Category 3 stations. Category 1 stations had significantly lower abundance of *Fucus* and total plant cover ($p < 0.10$; randomization t-test) than Category 3 stations. Category 2 stations had significantly higher total plant cover, number of plant taxa, *Mytilus* cover, and shells of dead *Mytilus* than Category 3 stations ($p < 0.10$; randomization t-test).

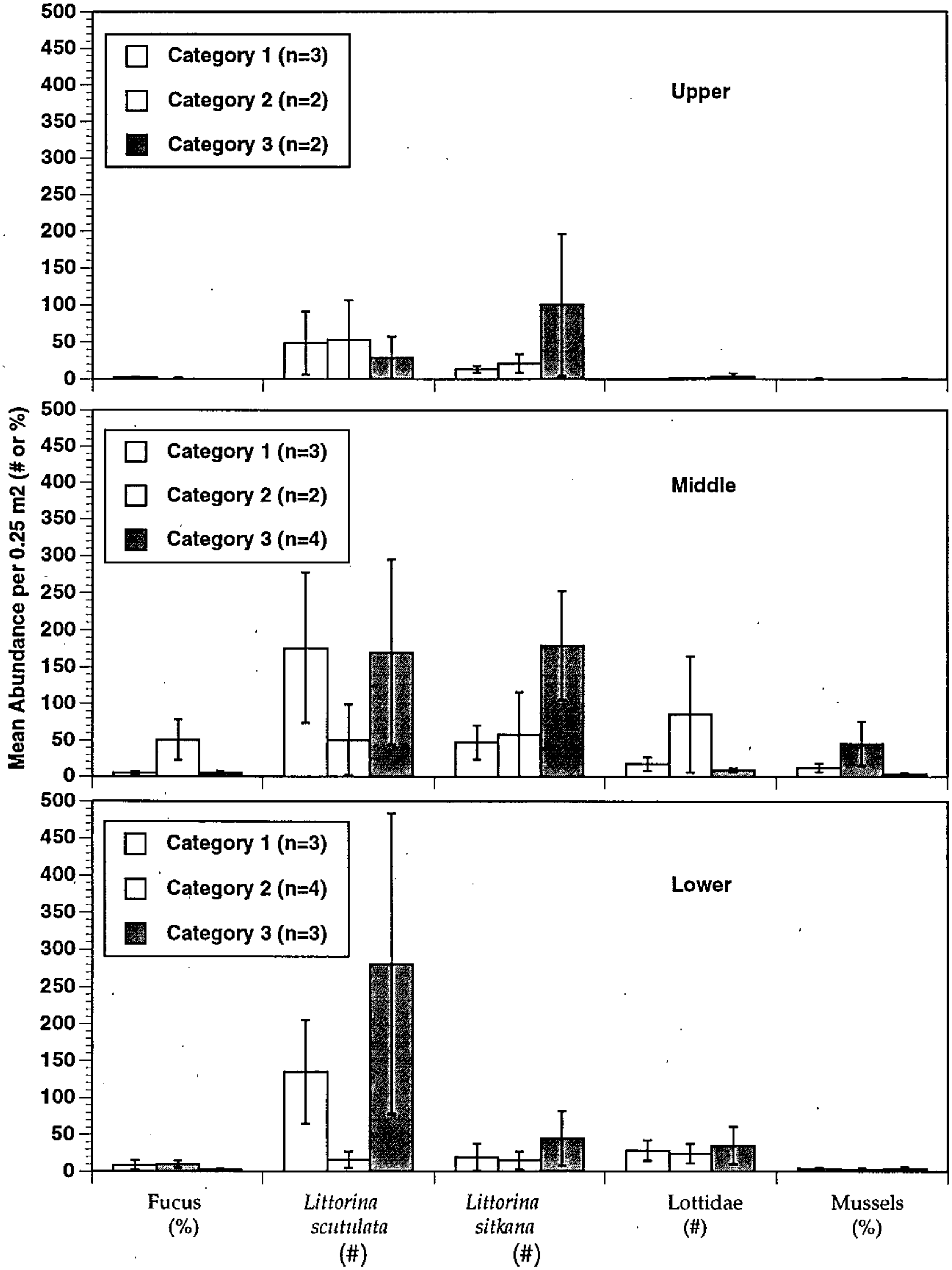

Figure 3-3. Mean abundance (± 1 SE) of major epibiota taxa at mixed soft sites, July 1992.

Lower Stations

The only taxa that had significant category effects at lower mixed-soft stations in a randomization ANOVA were *Leptasterias* and Nemertea ($p < 0.10$; Table 3-9). In randomization t-tests, however, Category 1 stations had significantly higher cover of filamentous red algae (e.g., *Polysiphonia, Pterosiphania*) than Category 3 stations ($p < 0.05$; Table 3-9), and Category 3 stations had significantly higher numbers of *Littorina scutulata* than the Category 2 stations ($p < 0.05$; Table 3-9). *L. sitkana* was also most abundant at the Category 3 stations, but this abundance was not significant in any of the statistical tests. Adult and juvenile limpets were about equal in numbers in all three categories (Figure 3-3; Table 3-9). Mean numbers of animal taxa were higher at both Category 1 and 2 sites than at Category 3 sites.

DISCUSSION

Because epibiota was sampled at only five boulder/cobble sites in 1992 and because the epibiota on mixed-soft substrata is more a function of the availability of cobbles at the surface of the sand/gravel matrix than of effects of oiling and treatment (Houghton et al.. 1993), the following discussions of epibiota are based primarily on data and observations in rocky habitats. Discussions of the definition of recovery used, the site selection strategy employed, and limitations of the statistical design of this study are provided in the report of 1991 monitoring results (Houghton et al. 1993) and are not repeated here.

General Biological Patterns

Protected and semi-protected rocky intertidal habitats within Prince William Sound support an attached and motile epibiota similar in many respects to that seen on other protected beaches throughout the Northeast Pacific (Ricketts et al., 1985; Nybakken, 1969; Kozloff, 1973). These areas are visually dominated by rockweed (*Fucus gardneri*) in the central portion of the intertidal zone between about mean high water and mean lower low water. In Prince William Sound a suite of common rockweed-associated fauna grouped consistently in cluster analyses performed on epibiota sampled in 1990 (Houghton et al., 1991a). These common taxa are mussels (*Mytilus*), littorine snails (two spp.), limpets (several spp.), and barnacles (primarily *S. balanoides*). They are frequently joined by the hermit crab (*Pagurus hirsutiusculus*), filamentous green algae (several taxa), and another barnacle (*Chthamalus dalli*).

Data from 1989 (ERCE et al., 1990a) showed that, before the spill, the assemblages at many Category 2 and 3 sites in this study had been typical of these assemblages at unoiled sites in the sound. Remnants of some of the dominant taxa (barnacle base plates, mussel byssus clumps, *Fucus* holdfasts) were evident at the two Category 3 rocky middle stations sampled in July 1990 (Houghton et al., 1991a). These remnants, coupled with the low occurrence of significant differences within this group of taxa among Category 1 and 2 sites throughout the sound, confirm that biota on Category 3 rocky beaches before treatment was similar to that on untreated beaches. The nature of the pretreatment community is also reflected by the evidence for survival of these dominant intertidal epibiota for several months on heavily oiled but as yet untreated beaches in 1989 (Lees et al., 1993). Even though prespill data are unavailable, conclusions about the effects of oiling and treatment on intertidal epibenthic assemblages were made by evaluating several types of information, including results from previous studies, temporal trends among sites within the three treatment categories, and results from multivariate analyses.

Previous studies of treatment effects following oil spills indicate that some cleanup methods often result in more short- and long-term ecological damage than oil itself (Smith, 1968; Foster and Holmes, 1977; Baca et al., 1987; Lees et al., 1993). Hot-water washing, steam cleaning, or sand blasting of oiled rocky shores can be expected to denude the rock surface of a great majority of biota (Lindstedt-Siva, 1979). Water temperatures commonly used for the *Exxon Valdez* cleanup (60°C on the vessels, probably slightly lower on the beach; Nauman, 1991) are well above the short-term lethal tolerances of temperate intertidal species (e.g., Graham et al., 1975). Water pressures generated through firehose nozzles, pressure-wash nozzles, and the multiport nozzles of the Omni-barge boom (to 7 kg/cm^2, 100 $pounds/in^2$) were likely sufficient, added to thermal stress, to dislodge all but the most firmly attached barnacles and algae. The fact that numerous statistically significant ($p < 0.05$) pre- to post-treatment changes were documented in two 1989 hot-water studies (Lees et al. 1993) attests to the biological effects of high-pressure hot water. Even in hot-water-washed beaches, patches of mussels and other biota can survive where protected from, or missed by, the direct force of the wash (e.g., the Block Island middle rocky station).

The high-pressure hot-water washes used to clean rocky beaches in Prince William Sound in 1989 eliminated the majority of the flora and fauna from large areas of shoreline (Houghton et al., 1990a; Lees et al., 1993). It does not appear, however, that the extent of rocky beaches denuded by the treatments was as great as in the *Torrey Canyon* cleanup, where washes were supplemented with a toxic dispersant (Southward and Southward, 1978). The dispersant reached into crevices and tide pools as it was swept along the beaches by long-shore currents; the result was nearly complete mortality of fauna and severe impacts to flora over extended continuous reaches. By contrast, in Prince William Sound variability in intensity of high-pressure hot-water treatment (horizontally and vertically) and refugia from direct washing in crevices and undersides of boulders prevented total mortality of the intertidal community in most areas.

By 1992 trends in mean abundance of many taxa at the three categories of sites had converged, indicating some recovery. Examples include *Fucus*, *Littorina sitkana*, and Lottiidae at middle rocky stations. Decreases over time were expected in the number of taxa showing significant category effects in ANOVAs. For example, the upper rocky stations had only one significant difference (encrusting Phaeophyta) among categories in 1992. At the middle stations the number of taxa showing significant category effects increased unexpectedly in 1992 compared to 1991; significant category effects were seen in two plant taxa and one animal taxon. This result compares with the finding of significant category effects in ANOVAs for five plant taxa in 1990 and one animal taxon in 1991 at middle rocky stations. Lower elevation sites had one plant taxon and two animal taxa with significant category effects (ANOVA) in 1992.

The increases in numbers of taxa showing significant effects at middle stations in 1992 may be due to changes in the mix of stations sampled, natural variation in abundances, or to chronic, delayed, or secondary effects of oiling and/or treatment. Southward and Southward (1978) provide examples of recovery of certain species that overshoots the species abundance in undisturbed systems; this may have happened with some species on high-pressure hot-water-washed sites in Prince William Sound (e.g., *Littorina scutulata,*). A longer assessment of the effects of oiling and treatment in Prince William Sound is necessary before final conclusions can be made about recovery of intertidal epibiota.

Algal Assemblages

Total plant cover, which includes all erect and crustose species, has not differed much over time except at the lower elevations, where the single Category 3 site has consistently had the lowest cover (Figure 3-4). Lower elevation sites have had higher total plant cover than the other two elevations. If erect species and crustose species are examined separately, however, a pattern emerges. In the year following treatment, middle and lower elevations at Category 3 sites had lower percentages of erect plant cover and higher encrusting algal cover than did other site categories (Figures 3-5 and 3-6). By July 1991 no significant differences existed among categories at middle stations, but the single lower Category 3 site (Northwest Bay Rocky Islet) continued to have higher encrusting cover and lower erect plant cover compared to the other two site categories. This condition was probably related to the intensive treatment this lower station received. In 1990 Northwest Bay Rocky Islet was colonized by opportunistic filamentous green and brown algae that may have retarded recovery of more typical species, particularly the longer-lived red algae (Figure 3-7). Replacement of the red algal assemblage at this site with *Fucus* and encrusting algae has left little open space and will likely inhibit the reestablishment of red algal assemblages for some time.

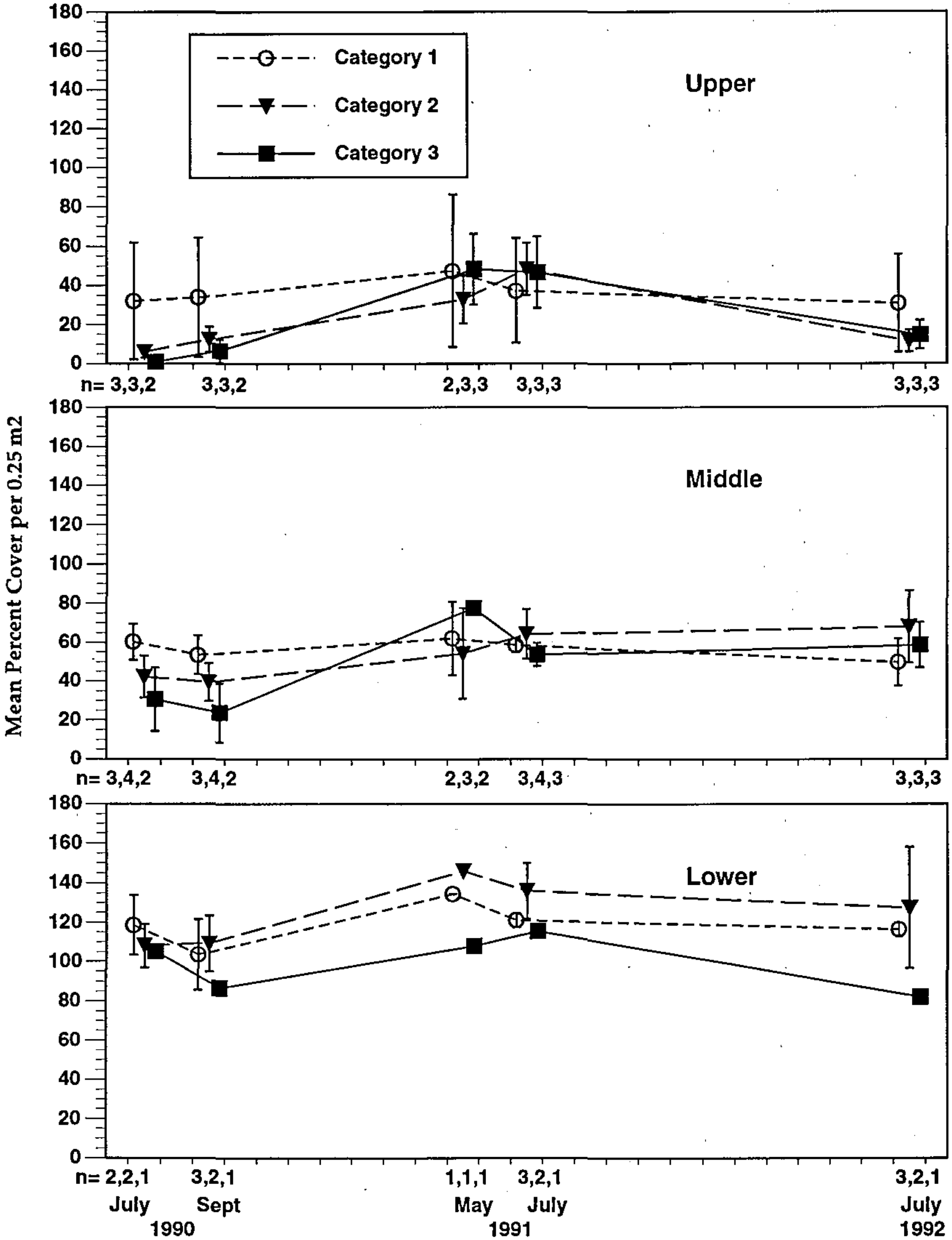

Figure 3-4. Mean percent cover (± 1 SE) of total plant cover from rocky sites, 1990-92. Number of stations sampled (n) shown below axis.

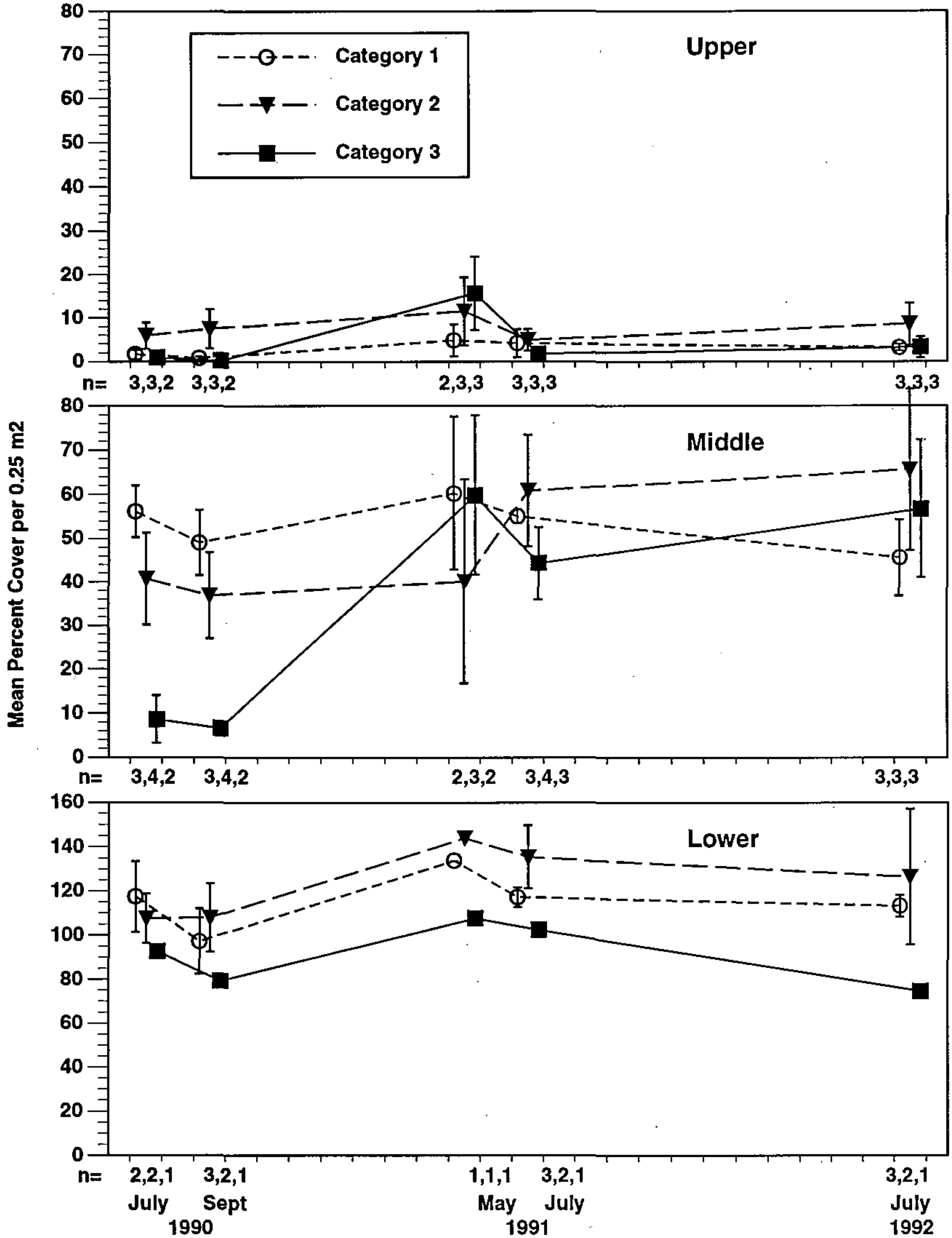

Figure 3-5. Mean percent cover (± 1 SE) of total plant cover from rocky sites 1990-92. Number of stations sampled (n) shown below axis.

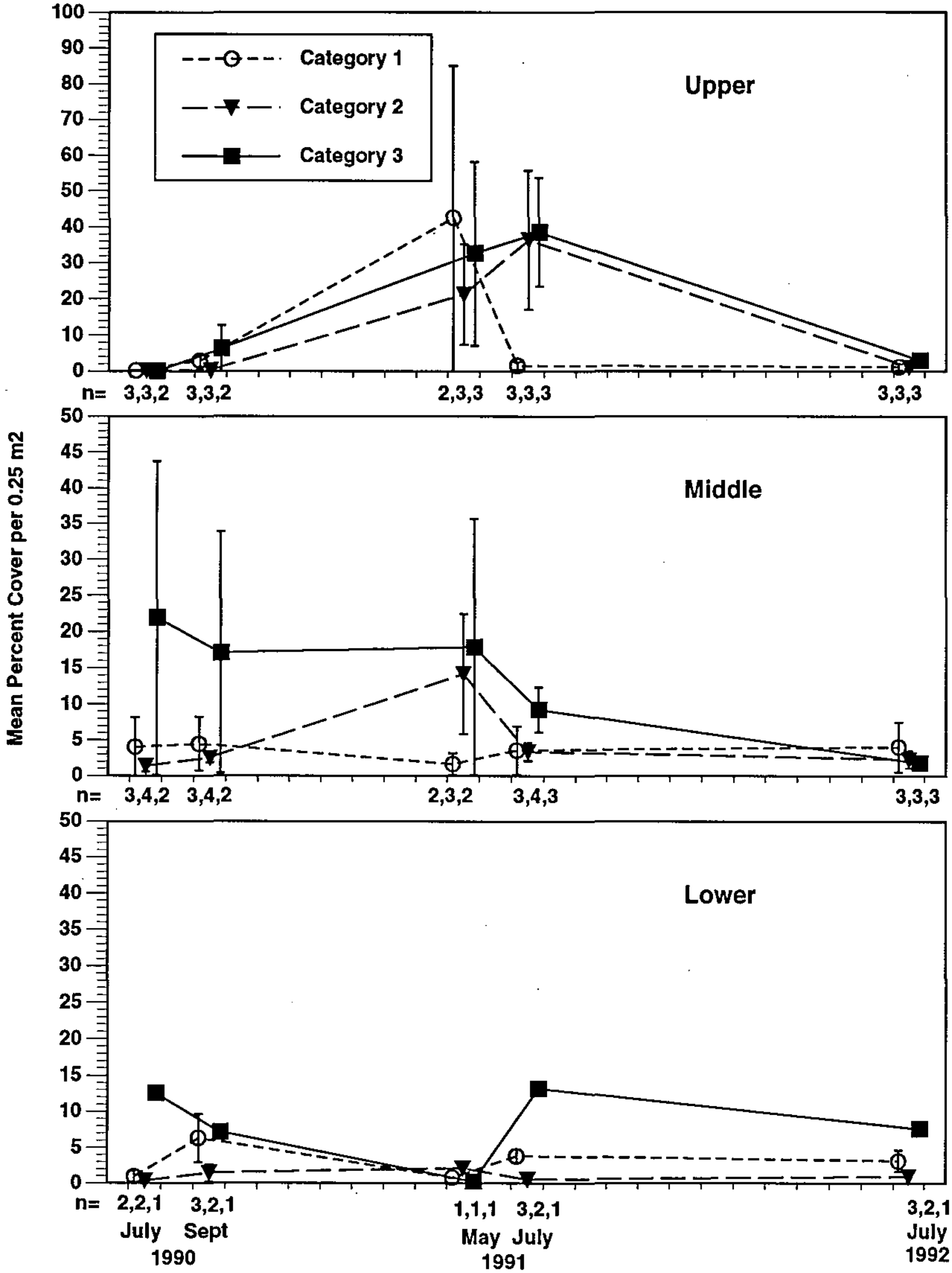

Figure 3-6. Mean percent cover (± 1 SE) of encrusting algal cover from rocky sites, 1990-92. Number of stations sampled (n) shown below axis. Note change of scale in upper.

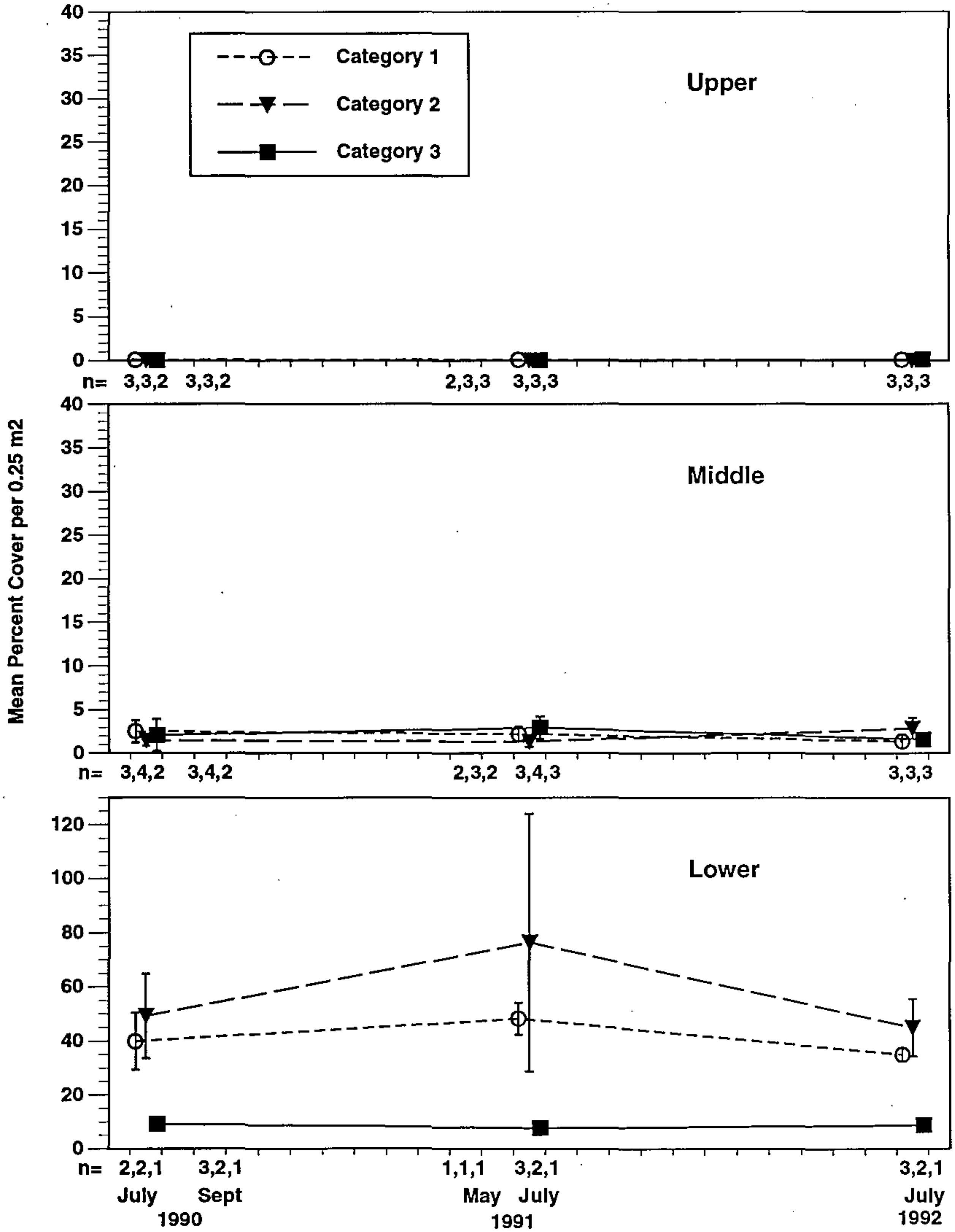

Figure 3-7. Mean percent cover (± 1 SE) of red algal cover from rocky sites, 1990-92 Number of stations sampled (n) shown below axis. Note change of scale in lower.

The number of plant taxa at rocky intertidal sites has not varied greatly among site categories over the course of this study except at lower stations, where there have been consistently more algal species at Category 1 stations (Figure 3-8). This greater richness may be due to the somewhat wider geographic separation of these sites (Hogg Bay, Crab Bay, Eshamy Bay) compared to the Category 2 and 3 rocky sites, which are all in the Knight Island and Naked Island groups. The increase in number of plant species at lower elevations in all site categories in July 1991 persisted into 1992 and appears to reflect some areawide phenomenon. Upper elevation Category 3 stations had few plants surviving treatment (1990), but a large number of spring colonizers at middle and upper rocky stations in May 1991 brought total plant richness at upper (and middle) elevations to levels comparable to, or greater than, those at Category 1 sites in July 1991 and 1992.

Fucus gardneri

The rockweed *Fucus gardneri* is one of the best indicators of the effects of oiling and high-pressure hot-water washing on Prince William Sound beaches. Exxon- sponsored studies in 1989 demonstrated the near-complete mortality of *Fucus* from several such treatments (Houghton et al., 1990a; Lees et al., 1993); moreover, the authors (Houghton and Lees) observed many additional areas in 1989 and 1990 where similar impacts to this species resulted from high-pressure hot-water washes.

Because upper stations in this study were placed at the upper limit of attached macrobiota, there is a high variability in microhabitats sampled and hence, in macroalgae. It is noteworthy that there has been virtually no recolonization by macroalgae at the south-facing Category 3 upper station at Northwest Bay Rocky Islet but noticeable recolonization at the north-facing Block Island Category 3 upper station (from 0.3 percent *Fucus* in May 1991 to 4.1 percent in July 1992). Stekoll et al. (1993) and van Tamelen and Stekoll (1993) also reported that damage to *Fucus* from oiling (and treatment) in Prince William Sound occurred mainly in the upper intertidal and that recovery of *Fucus* in the upper intertidal is proceeding slowly.

Sporeling cover was relatively constant at Category 1 middle stations and thus reflected a continuing potential for replacement of senescing plants (Figure 3-9). In July of both 1990 and 1991, sporeling establishment at Category 2 and 3 middle stations was higher than at Category 1 middle stations and predicted the ensuing recovery of larger plants. Through early spring of 1991, the abundance of larger, post-sporeling *Fucus* plants (generally those larger than 1 to 2 cm long) at Category 2 middle rocky stations was noticeably, but not significantly, depressed below that at Category 1 middle stations (Figure 3-10). By July 1991 differences in *Fucus* cover between Category 1 and 2 had disappeared; cover at Category 3 stations remained significantly depressed.

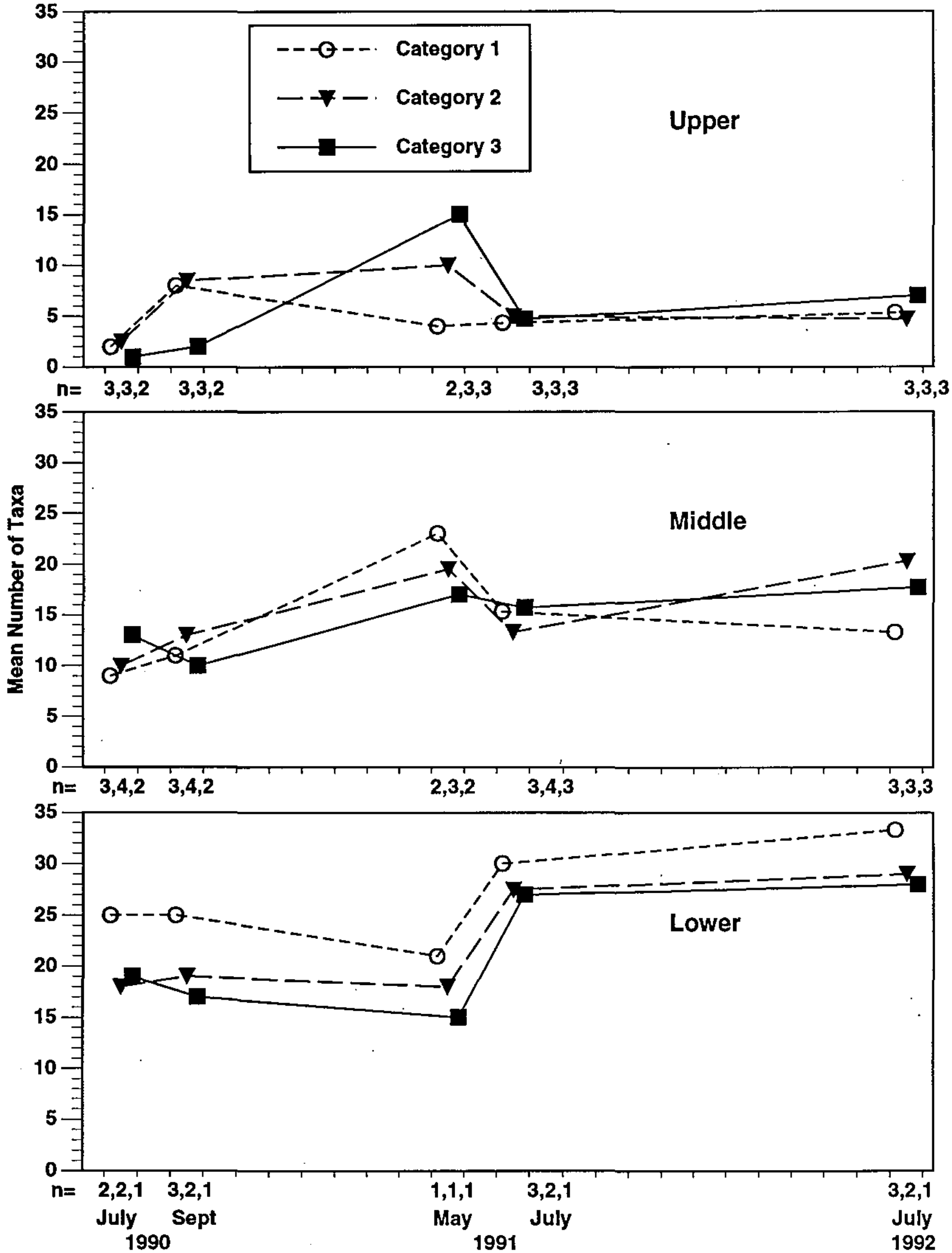

Figure 3-8. Mean number of plant taxa for each category at three stations. Number of stations sampled (n) shown below axis.

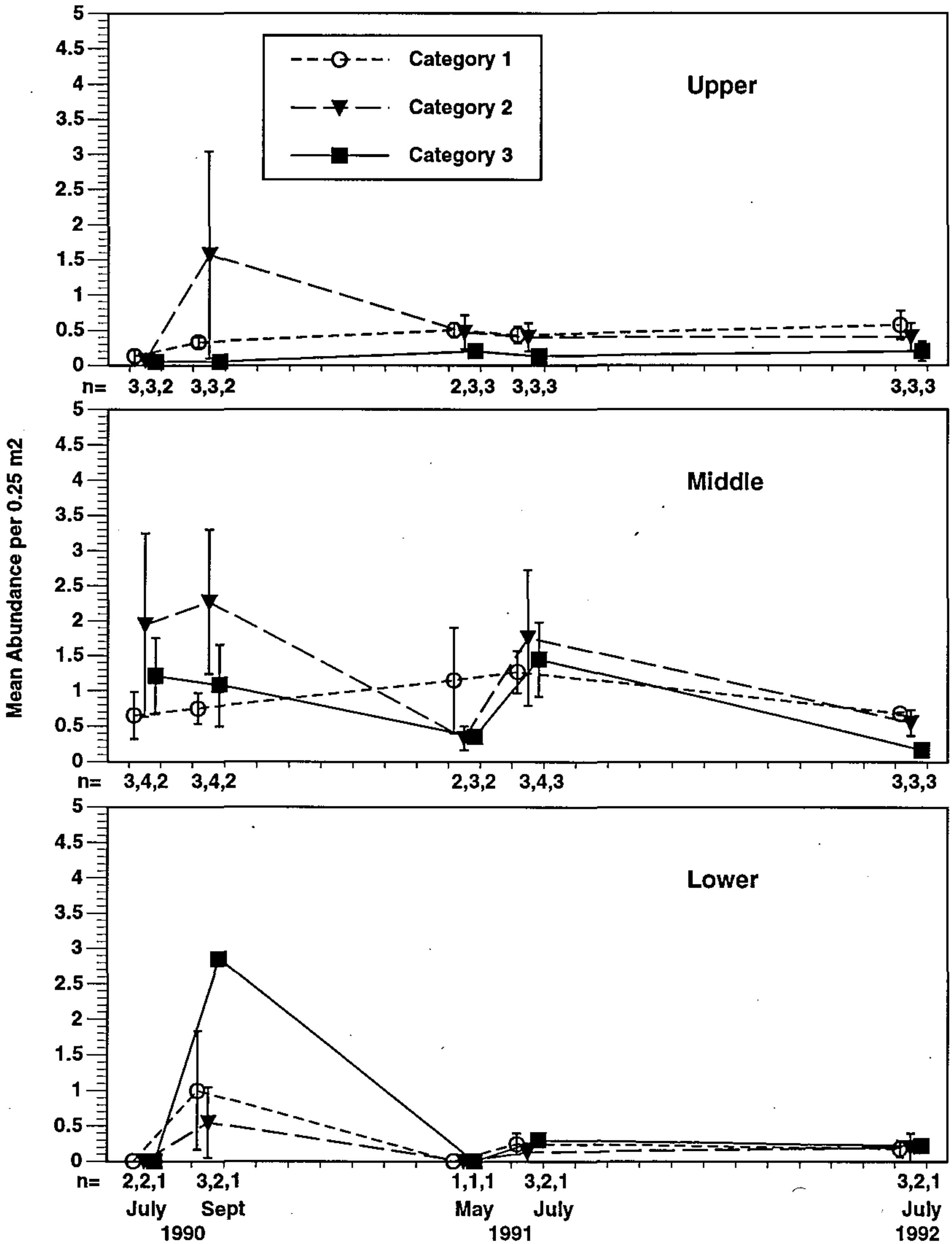

Figure 3-9. Mean abundance (± 1 SE) of *Fucus* sporelings from rocky sites, 1990–92. Number of stations sampled (n) shown below axis.

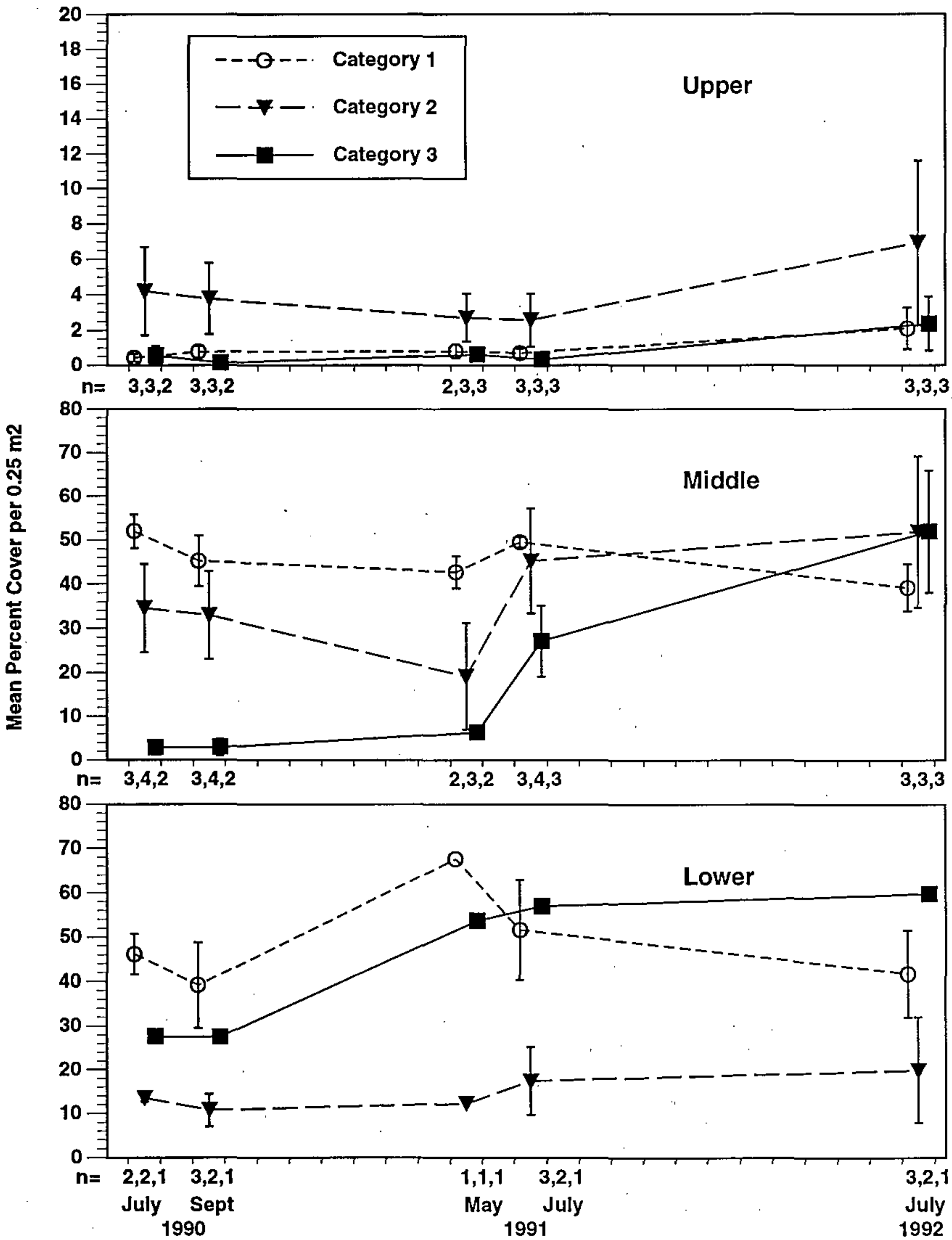

Figure 3-10. Mean percent cover (± 1 SE) of *Fucus gardneri* from rocky sites, 1990–92. Number of stations sampled (n) shown below axis. Note change of scale in upper.

By the summer of 1992, *Fucus* cover at Category 3 middle rocky stations had doubled from that in 1991, and there were no longer any significant category differences (Figure 3-10). The rate of recovery has varied substantially among the high-pressure hot-water washed sites. The Block Island middle rocky station, which faces north, experienced only partial mortality of *Fucus* in 1989 and had recovered from 4.6 percent cover (including sporelings) in 1990 to 77.8 percent in 1992. At the Northwest Bay Rocky Islet site, cover doubled from July 1991 (11.3 percent) to 1992 (24.3 percent); substantial recovery occurred on the outer portion of the station's transect line, which has numerous cracks in the rock where *Fucus* sporelings became established in 1990 and 1991 (see Figure 41 in Houghton et al., 1993). The inner part of the transect crosses a relatively smooth rock bench with few cracks or depressions; this part of the middle station remained nearly as devoid of *Fucus* in 1992 as it has been since treatment in June of 1989. Prior to treatment (May 1989) this station had 79.6 percent cover (ERCE et al., 1990a), so recovery to pretreatment conditions is far from complete.

Recovery of *Fucus* would have been much greater had high-pressure hot-water washes not led to the complete removal of the holdfasts. McCook and Chapman (1992) found that damaged holdfasts of two other species of *Fucus* sprouted adventitious shoots even when basal tissue had been cut to a thickness of only 2 mm. In most cases, *Fucus* at Category 2 sites in this study regenerated from vegetative growth of surviving plants, stems, or holdfasts, while at Category 3 sites, recovery resulted primarily from settlement and growth of sporelings, a much slower process. Moreover, Stekoll et al. (1993) showed that loss of a majority of mature plants at affected sites greatly reduced the rate of settlement of *Fucus* zygotes; van Tamelen and Stekoll (1993) also showed that zygotes were more likely to settle in cracks and crevices than on smooth surfaces. Both of these observations are consistent with findings in this study.

Fucus cover at the Category 2 lower stations has remained low compared to the other site categories (Figure 3-10). This is due to the relatively minor impact of oil at lower stations and the high percent cover of erect red algae (Figure 3-7; includes all nonencrusting Rhodophyta except Endocladiaceae); these taxa normally dominate algal cover in the lower intertidal (Figure 3-7). Erect reds were removed from the one lower elevation Category 3 station at Northwest Bay Rocky Islet and have not recovered to date. *Fucus* has thus been able to extend its dominance downward into unoccupied space, as seen in the settlement of sporelings at this station in September 1990 (Figure 3-9) and the subsequent increase in cover of larger *Fucus* at this station from 21 percent in 1990 to 59.6 percent in 1992 (Figure 3-10). Pretreatment (May 7, 1989) *Fucus* cover at this station was only 15.4 percent (ERCE et al., 1990a).

<u>Endocladiaceae</u>

The Endocladiaceae showed a significant category effect in 1990 with higher percent cover at the Category 3 middle stations; no category effect was seen in 1991. In 1992 the

Endocladiaceae again showed category differences with cover at Category 3 middle stations again significantly higher than at Category 1 sites. The family Endocladiaceae in Prince William Sound is represented by *Endocladia muricata*, primarily found at upper elevations, and *Gloiopeltis furcata*, an opportunistic early settling species also normally found at upper elevations. In 1990 through 1992, *Gloiopeltis* was found mainly in its normal distributional range at upper stations at Category 1 and 2 sites; in July 1991 this species was most abundant at middle stations at Category 3 sites (Figure 3-11). Temporary increases in abundance of this species at Category 3 middle stations were likely a reflection of the increase in space available for settlement following high-pressure hot-water treatment. *Gloiopeltis* cover declined at Category 3 sites following sharp increases in *Fucus* cover in July 1992. The opportunistic nature of this species may also be inferred from the paired Northwest Bay West Arm rocky sites in this study (Chapter 6) and from the studies of Stekoll et al. (1993), who noted higher cover of this species at their oiled sites than at unoiled control sites.

Other Red Algae

Nonencrusting red algae are typical understory plants at middle elevations on rocky shores in Prince William Sound and may dominate the substratum at lower elevations. There were no significant category effects in distributions of red algae (all erect taxa other than Endocladiaceae) at upper or middle elevation stations.

The effect of high-pressure hot-water washing on red algae at middle elevations is perhaps best illustrated by the changes seen at two sites in Northwest Bay. Sampling at the side-by-side Category 3 and reference rocky sites in the West Arm (Houghton et al., 1993) showed a nearly total absence of the typical understory species (*Mastocarpus papillata, Neorhodomela* spp.) at the middle Category 3 station in 1991. No recovery of these taxa had occurred by 1992 despite the substantial recovery of the *Fucus* overstory (see Chapter 6).

In May 1989, more than a month after the spill, the Northwest Bay Rocky Islet lower rocky station had a cover of 73.9 percent of nonencrusting red algal taxa (ERCE et al., 1990a). Following treatment, cover of these taxa dropped to 18.8 percent in June 1989 and declined further to 10.9 percent by September 1989 (ERCE et al., 1990b). From July 1990 through June/July 1992, cover has remained less than 10 percent. At a similarly oiled and treated lower rocky station first sampled in July 1992 (Mussel Beach North), dominance of red algae that was photodocumented in 1989 before treatment had recovered (or maintained) a much greater cover (> 40 percent) of erect red algae. The greater abundance of red algae at Category 2 lower rocky stations throughout the study (Figure 3-7) is largely the result of the absence of spill-related impacts and site differences, with especially high abundance (> 90 percent) at Outside Bay.

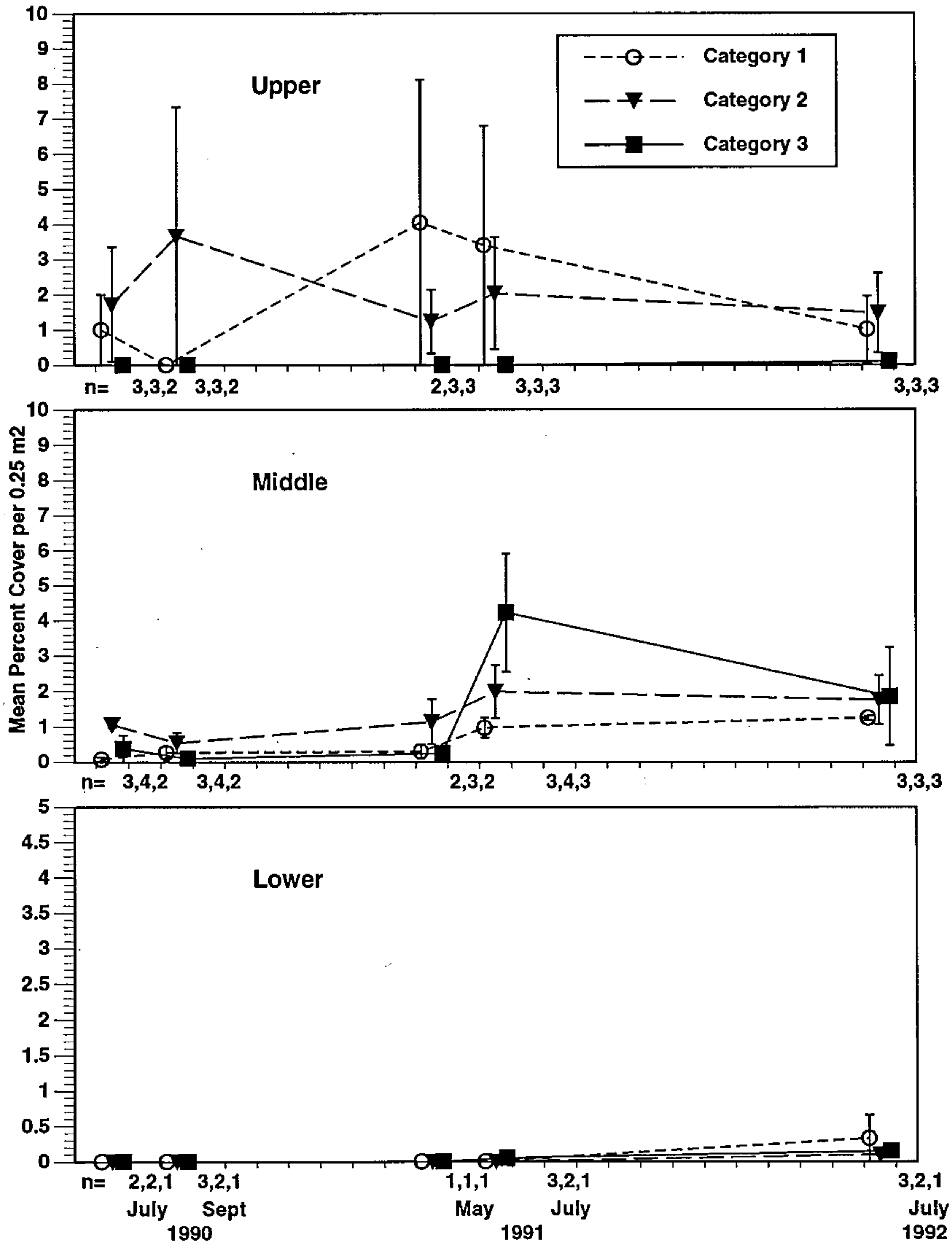

Figure 3-11. Mean percent cover (± 1 SE) of *Gloiopeltis furcata* from rocky sites, 1990–92. Number of stations sampled (n) shown below axis. Note change of scale in lower.

Severe impacts from high-pressure hot-water washes on encrusting and articulated coralline algae are indicated by observations of large areas of whitened corallines in the Knight Island group in late 1989 and throughout 1990 (J. P. Houghton, Pentec Environmental, Inc., personal observation) and by data from the lower station at the Northwest Bay Rocky Islet site. Coralline algae visible immediately after cleaning (June 1989; 2.3 percent articulated; 8.9 percent encrusting; ERCE et al., 1990b) were all dead by September 1989 and have remained largely absent since (< 1 percent by 1992; Table 3-3).

Invertebrate Assemblages

The mean number of invertebrate taxa on rocky shores in Prince William Sound has been consistently higher at unoiled (Category 1) sites at all elevations than at oiled sites (Figure 3-12). This relationship has diminished over time, however, and no significant category effects were seen in ANOVAs at any elevation in 1992. The increased mean faunal richness at middle and upper elevations beginning in 1991 is due in part to the initiation of identification of limpets (Lottiidae) to the species level, where possible.

No significant category effects remained in 1992 in randomization ANOVAs of abundances of dominant invertebrate taxa at upper rocky stations. Only one taxon (*Pagurus hirsutiusculus*) had a significant category effect at the middle rocky stations; at lower rocky stations significant differences among categories were seen in three animal taxa.

Littorina scutulata and *Littorina sitkana*

Like rockweed, littorine snails were severely impacted by short-term applications of high-pressure hot-water washes (Lees et al., 1993) and appear to be good indicators of this stress. Recovery patterns of the two species have differed markedly, however, and thus reflect their different ecological strategies.

Littorina scutulata abundances at middle and lower stations have been much higher in 1991 and 1992 at Category 3 sites than at the other site categories (Figure 3-13). At upper rocky stations *L. scutulata* recovered from near absence at Category 3 sites in July 1990 to be most abundant at these sites in 1992. The increase in numbers of *L. scutulata* at Category 3 sites following disturbance was not surprising since this species releases pelagic larvae (Behrens, 1972) and feeds primarily on diatom films, lichen crusts, and macroscopic algae (Castenholz, 1961; Behrens-Yamada, 1989). *L. scutulata* was observed feeding on the early colonizing diatom and blue-green crust at the Category 3 Northwest Bay Rocky Islet site, especially in a flat bench area of the middle station and on the upper station where little or no macroalgae was present.

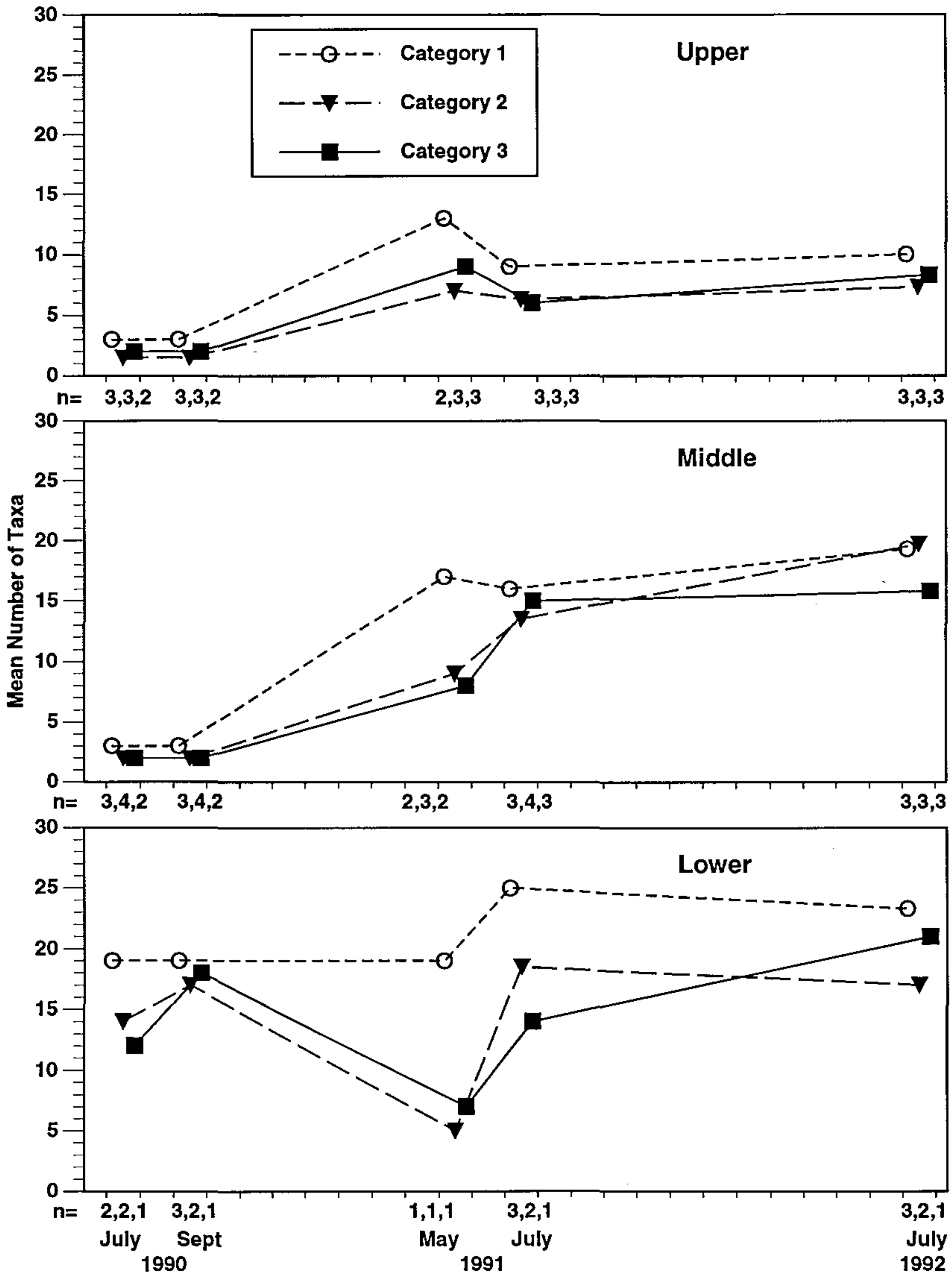

Figure 3-12. Mean number of animal taxa for each category at three elevations. Number of stations sampled (n) shown below axis.

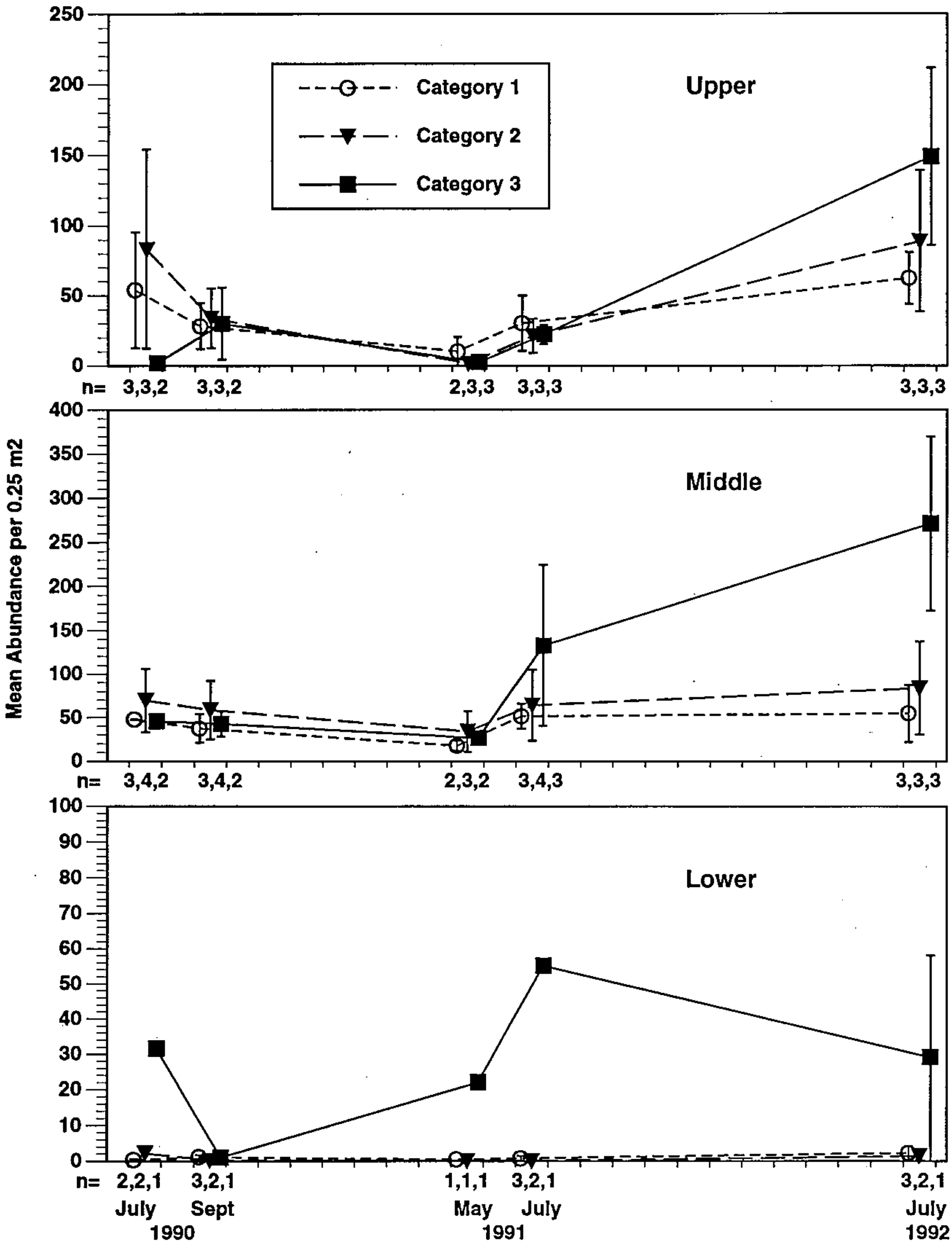

Figure 3-13. Mean abundance (± 1 SE) of *Littorina scutulata* adults from rocky sites, 1990–92 Number of stations sampled (n) shown below axis. Note different scale for each elevation.

Littorina sitkana abundances at the Category 3 upper stations were relatively high in July 1990 (Figure 3-14), primarily because of concentrations of large individuals among boulders at the Mussel Beach South rocky site. This species prefers crevices and wave-protected areas (Behrens, 1972; Behrens-Yamada, 1989) and appears to have survived oiling and subsequent treatment at this site because of these habitat preferences. Numbers at Category 3 upper stations declined through the winter of 1990-91, but by July 1991 densities again exceeded those at other site categories.

At middle elevations at Category 3 sites, *L. sitkana* densities reflected the impacts of high-pressure hot-water washes and were very low in 1990 and early 1991; numbers increased somewhat in July 1991 and matched the abundance at other site categories by July 1992 (Figure 3-14). This species produces benthic, gelatinous egg masses from which juveniles hatch directly (Behrens-Yamada, 1989); thus, it was expected that recovery of this species would be slow, especially in areas where macroalgae abundances are also low. Both *L. sitkana* and *L. scutulata* tend to occupy upper and middle elevations and are much less abundant at lower elevations, where they are subjected to heavy predation (Williams, 1992). Numbers of both species at lower stations were highest at Category 3 sites, especially in 1991, probably because of reduced predator abundance.

Rolan and Gallagher (1991) reported no apparent effects on littorines following heavy oiling of a shoreline in Sullom Voe (Shetland Islands). The reductions in grazers such as littorines and limpets that often occur following spills (Southward and Southward, 1978; National Research Council, 1985) can be expected to result in rapid growth of opportunistic algae, however, as was observed at many areas in Prince William Sound in spring of 1990.

Lottiidae

Limpets (lumped as Lottiidae) also suffered nearly total mortality in the high-pressure hot-water-wash tests reported by Lees et al. (1993). Based on these results, Prince William Sound monitoring by Highsmith et al. (1993), and patterns seen in 1990 and 1991 data (Houghton et al., 1993), this group appears to be good indicator of stresses from both oiling and hot-water treatment.

At upper rocky stations in this study, the fact that very few limpets have been seen over all three years at Category 2 and 3 upper stations indicates that both oiling and high-pressure hot-water washing were damaging. In contrast, the fact that virtually no difference in limpet abundance has been observed over time between Category 1 and 2 middle stations suggests that effects from oiling alone were relatively minor. The depressed abundances throughout 1990 and early 1991 at Category 3 sites indicate significant impacts from high-pressure hot-water washes. Numbers at Category 3 middle stations gradually increased in the summer of 1991 (Figure 3-15), and by summer of 1992, they equaled those at the Category 1 and 2 sites. Many limpets at all site categories were juveniles in 1992, though Category 2 sites had the most juveniles (Table 3-2).

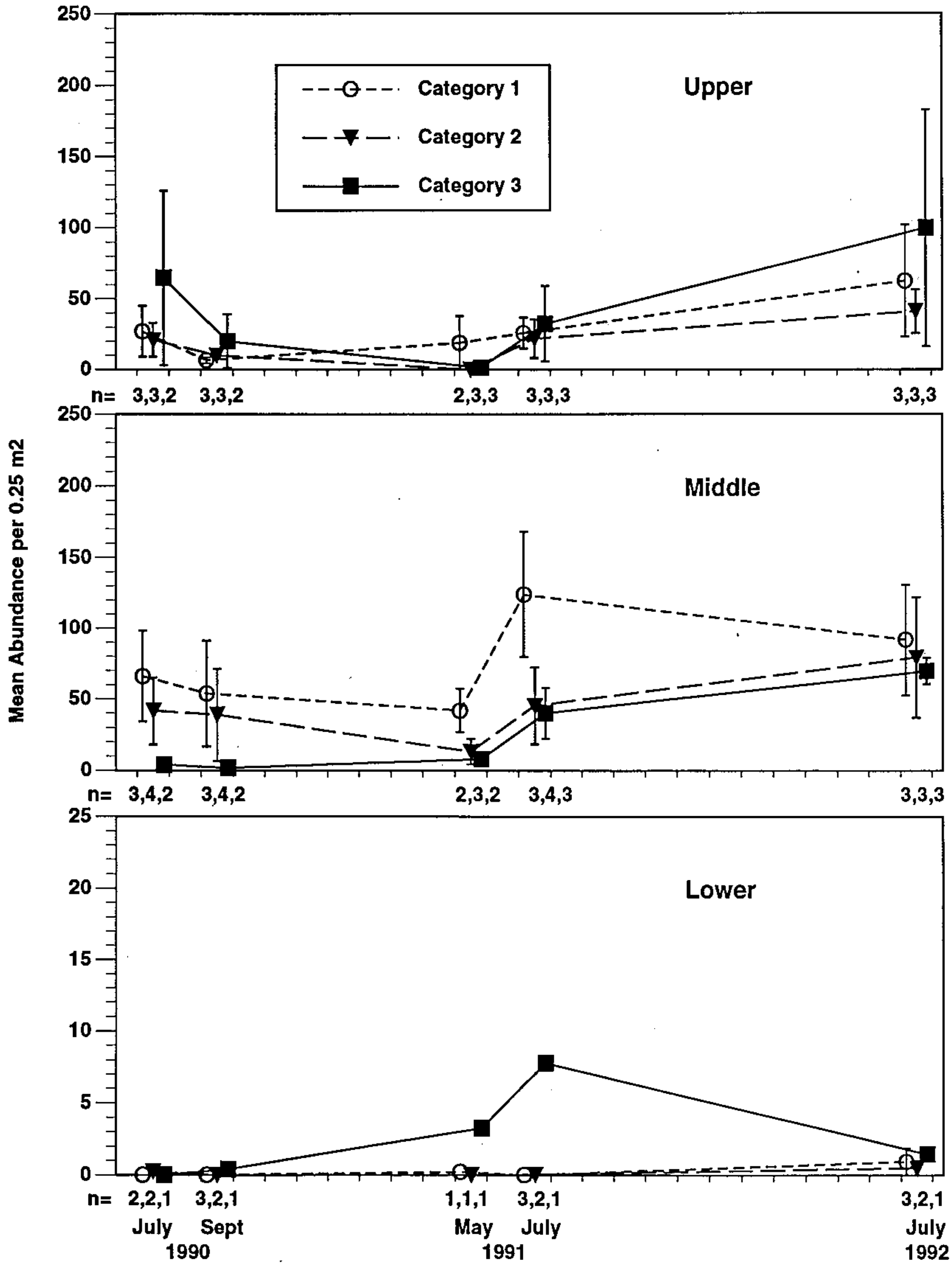

Figure 3-14. Mean abundance (± 1 SE) of *Littorina sitkana* adults from rocky sites, 1990–92. Number of stations sampled (n) shown below axis. Note change of scale in lower.

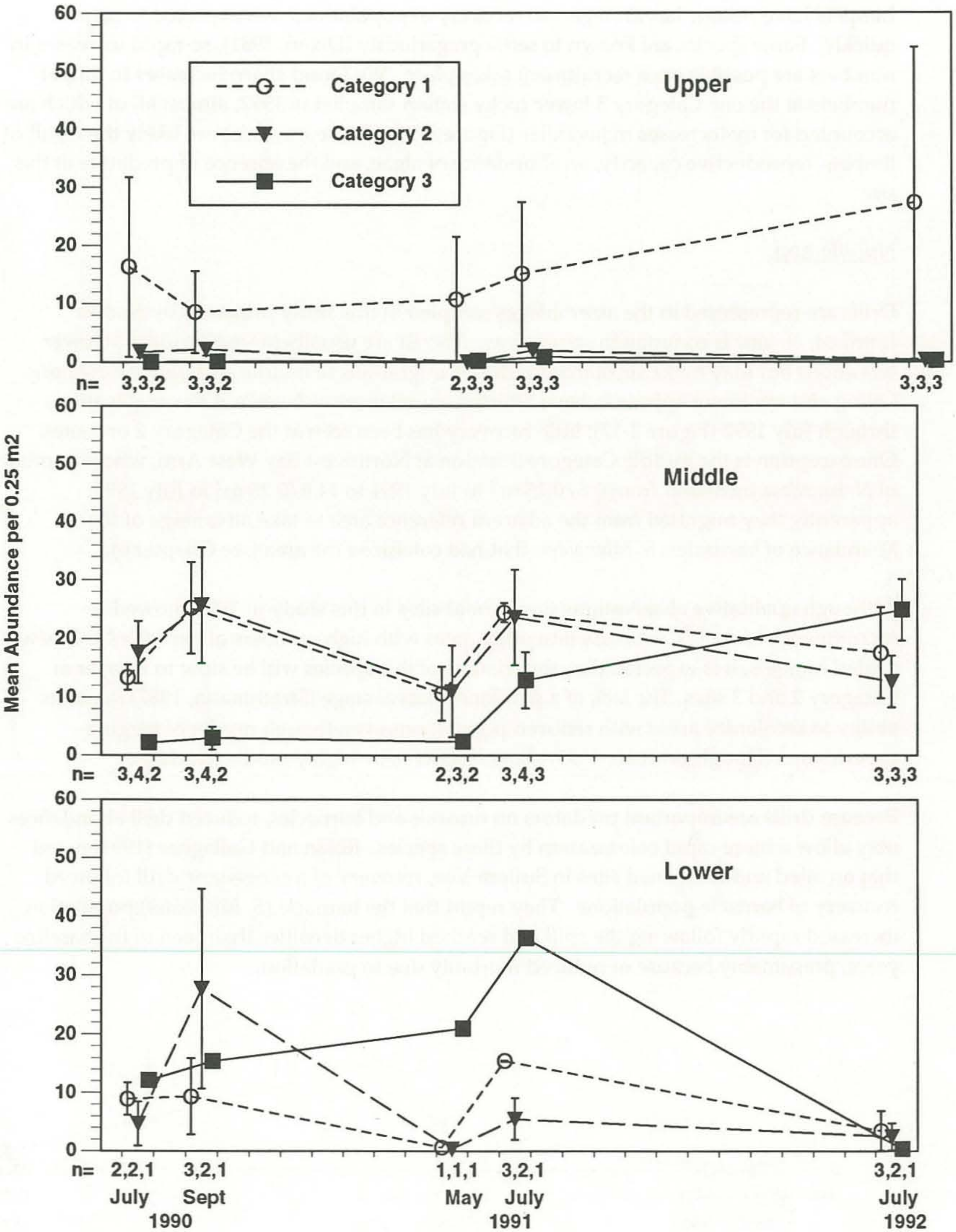

Figure 3-15. Mean abundance (± 1 SE) of *Lottidae* adults from rocky sites,1990–92. Number of stations sampled (n) shown below axis.

Limpets have pelagic larval stages, so recovery of populations was expected to occur quickly. Some species are known to settle gregariously (Dixon, 1981), so rapid increases in numbers are possible once recruitment takes place. We found sharp increases in limpet numbers at the one Category 3 lower rocky station sampled in 1992, almost all of which are accounted for by increases in juveniles (Figure 3-16). These increases are likely the result of limpets' reproductive capacity, an abundance of algae, and the absence of predators at this site.

Nucella spp.

Drills are represented in the assemblages sampled in this study primarily by *Nucella lamellosa*; *N. lima* is common in some areas. *Nucella* are usually more abundant at lower elevations but may make substantial foraging migrations to middle and upper elevations. Oiling and treatment appear to have affected abundances of *Nucella* at lower elevations through July 1992 (Figure 3-17); little recovery has been seen at the Category 2 or 3 sites. One exception is the middle Category 3 station at Northwest Bay West Arm, where numbers of *N. lamellosa* increased from 0.6/0.25 m^2 in July 1991 to 14.6/0.25 m^2 in July 1992; apparently they migrated from the adjacent reference area to take advantage of the abundance of barnacles, *S. balanoides*, that had colonized the area (see Chapter 6).

Although qualitative observations throughout sites in this study in 1992 showed recruitment of small *N. lamellosa* into other areas with high numbers of barnacles and newly settled mussels, it is expected that abundances of this species will be slow to recover at Category 2 and 3 sites. The lack of a planktonic larval stage (Strathmann, 1987) limits its ability to recolonize areas with reduced populations even though results of tagging experiments (Houghton et al., 1993) show *Nucella* to be highly motile as adults.

Because drills are important predators on mussels and barnacles, reduced drill abundances may allow a more rapid colonization by these species. Rolan and Gallagher (1991) noted that on oiled and uncleaned sites in Sullom Voe, recovery of a congeneric drill followed recovery of barnacle populations. They report that the barnacle (*S. balanoides*) population increased rapidly following the spill and reached higher densities than seen in the baseline years, presumably because of reduced mortality due to predation.

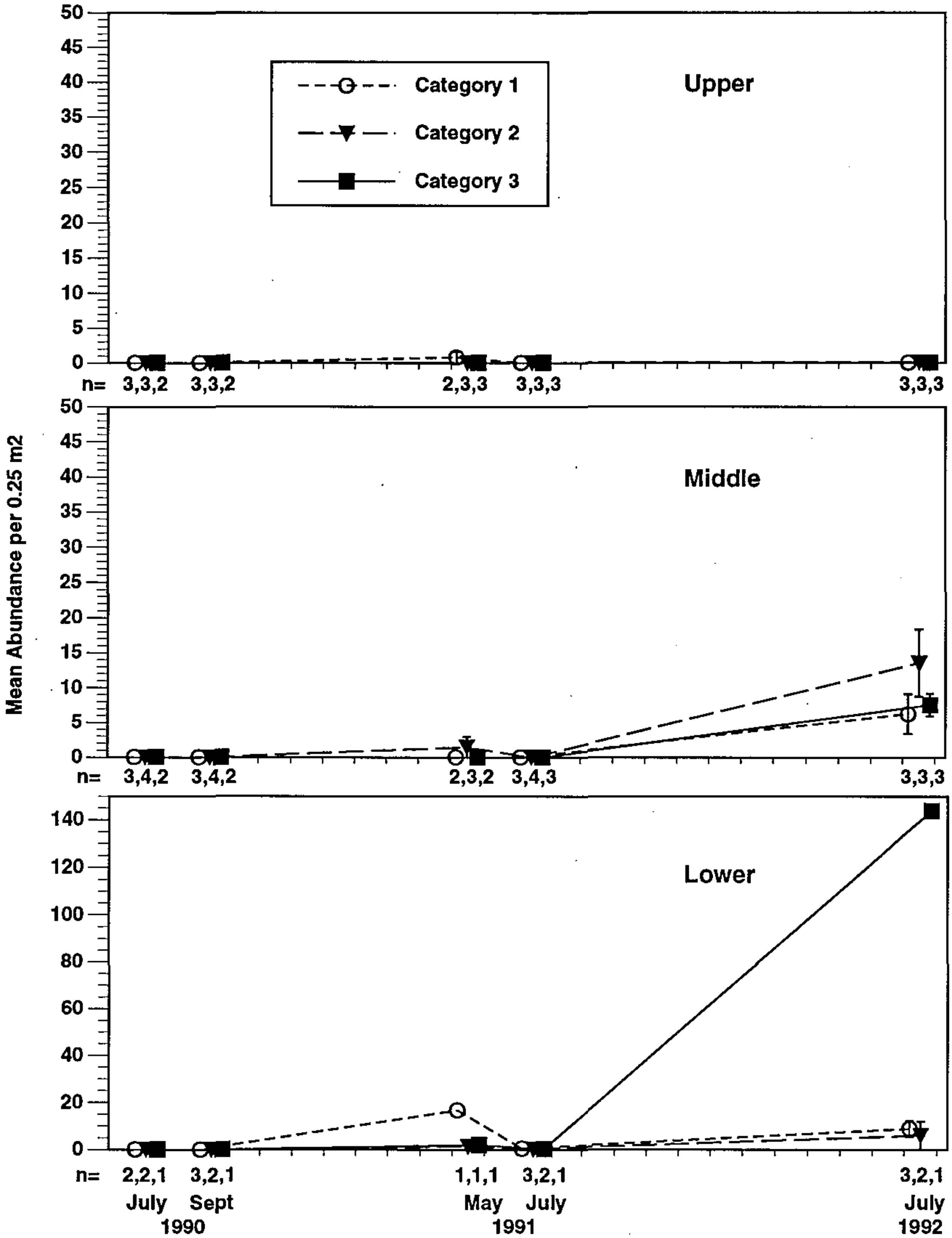

Figure 3-16. Mean abundance (± 1 SE) of *Lottidae* juveniles from rocky sites, 1990–92. Number of stations sampled (n) shown below axis. Note change of scale in lower.

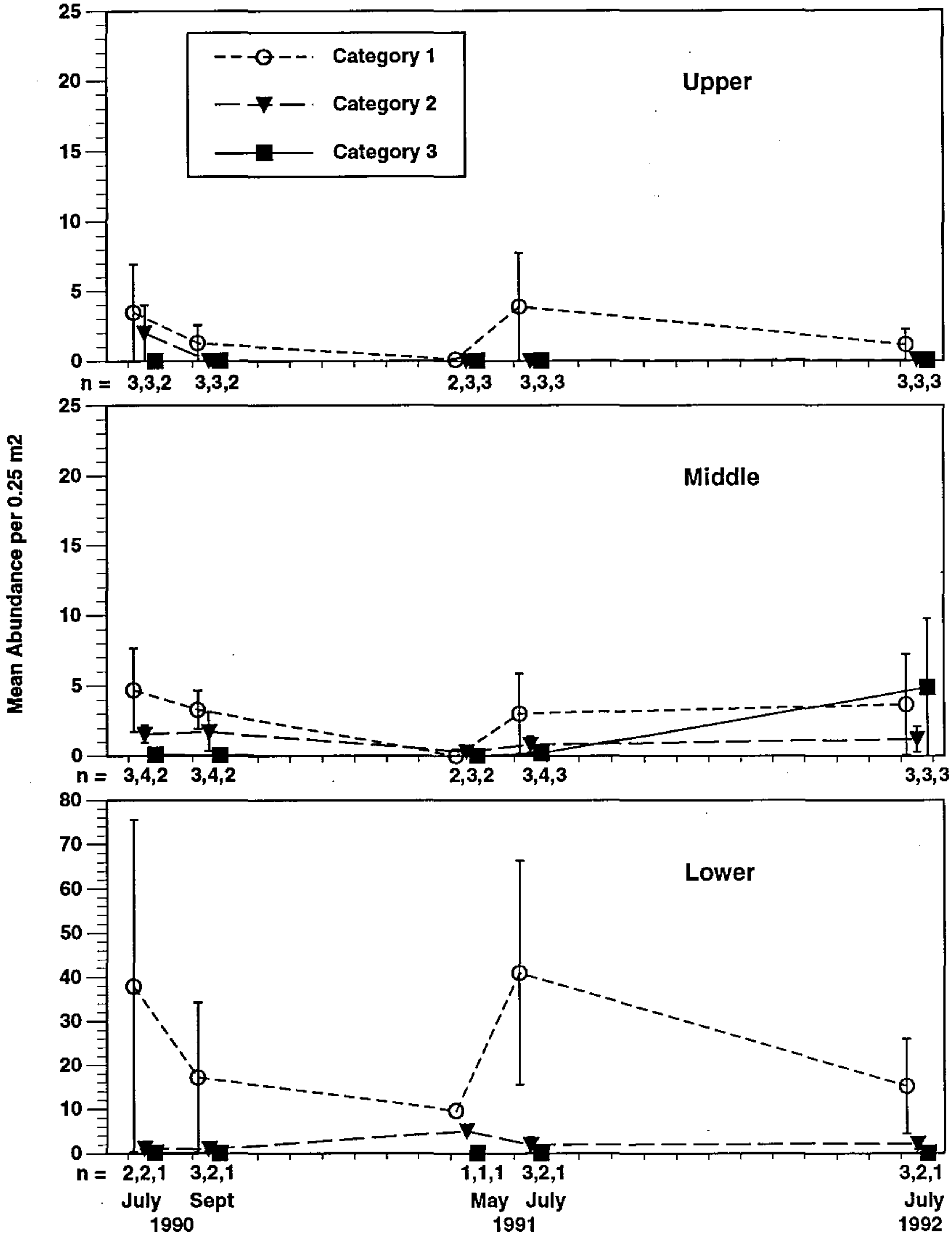

Figure 3-17. Mean abundance (± 1 SE) of *Nucella* spp. from rocky sites, 1990–1992. Number of stations sampled (n) shown below axis. Note change of scale in lower.

Pagurus spp.

Hermit crabs, *Pagurus* spp., are important scavengers of the middle and lower elevations of rocky and mixed-soft intertidal habitats in Prince William Sound. Large aggregations are often found in association with any large detritus (e.g., salmon carcasses) or in refugia under rocks or in tidepools.

This genus was less abundant (but not significantly so) at Category 2 and 3 middle rocky stations in 1990 (Figure 3-18), possibly because of mortalities from oiling and/or treatment. An increase in numbers of *P. hirsutiusculus* in 1992 at middle elevation Category 1 sites resulted in a significant category effect in an ANOVA; there were also significant differences between Category 1 and both Category 2 and Category 3 in t-tests. Because there were no significant differences in abundance among categories in either 1990 or 1991, it is unlikely that the significant differences in 1992 are explained by oiling or treatment impacts.

Large increases of this species were also seen at the lower elevation Category 3 site in 1991 and 1992 (Figure 3-18). Since *Pagurus* is motile, concentrations of this species on food resources or for reproductive purposes or for exchange of shells could have resulted in these aggregations.

Barnacles (*Balanomorpha*)

At upper rocky stations the opportunistic barnacle *Chthamalus dalli* was consistently found at higher abundances at the Category 1 sites (Figure 3-19). At middle stations a major set occurred at Category 2 and 3 sites between May and July 1991, and *Chthamalus* remained more abundant at these sites through 1992. The percent cover for all species of barnacles combined at upper stations was consistently highest at Category 1 sites (Figure 3-20). This is explained in part by the set of another opportunistic barnacle, *Semibalanus balanoides*, in the spring of 1991. *S. balanoides* also successfully recruited to the lower Category 1 and 2 stations in 1990 and 1991 and to the middle Category 3 stations in 1991 (Figure 3-21). Because of this high abundance of *S. balanoides*, Category 3 middle stations had more total barnacles (Balanomorpha) in 1991 and 1992 (Figure 3-20). At the single lower elevation Category 3 station at Northwest Bay Islet, this species successfully colonized available space in 1990 and 1991 but disappeared by July 1992, probably as a result of predation as biological controls became reestablished.

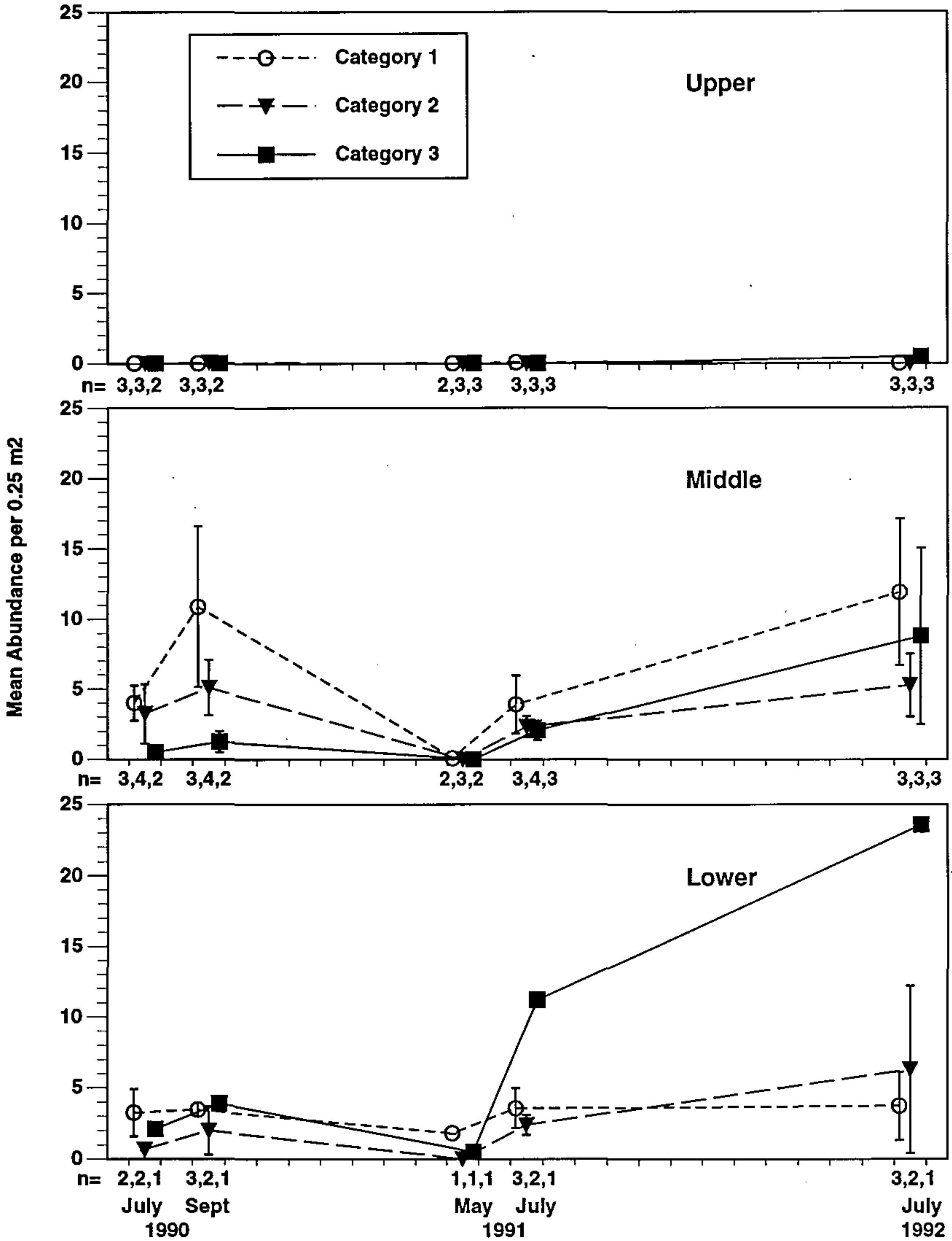

Figure 3-18. Mean abundance (± 1 SE) of *Pagurus* spp. from rocky sites, 1990–92. Number of stations sampled (n) shown below axis.

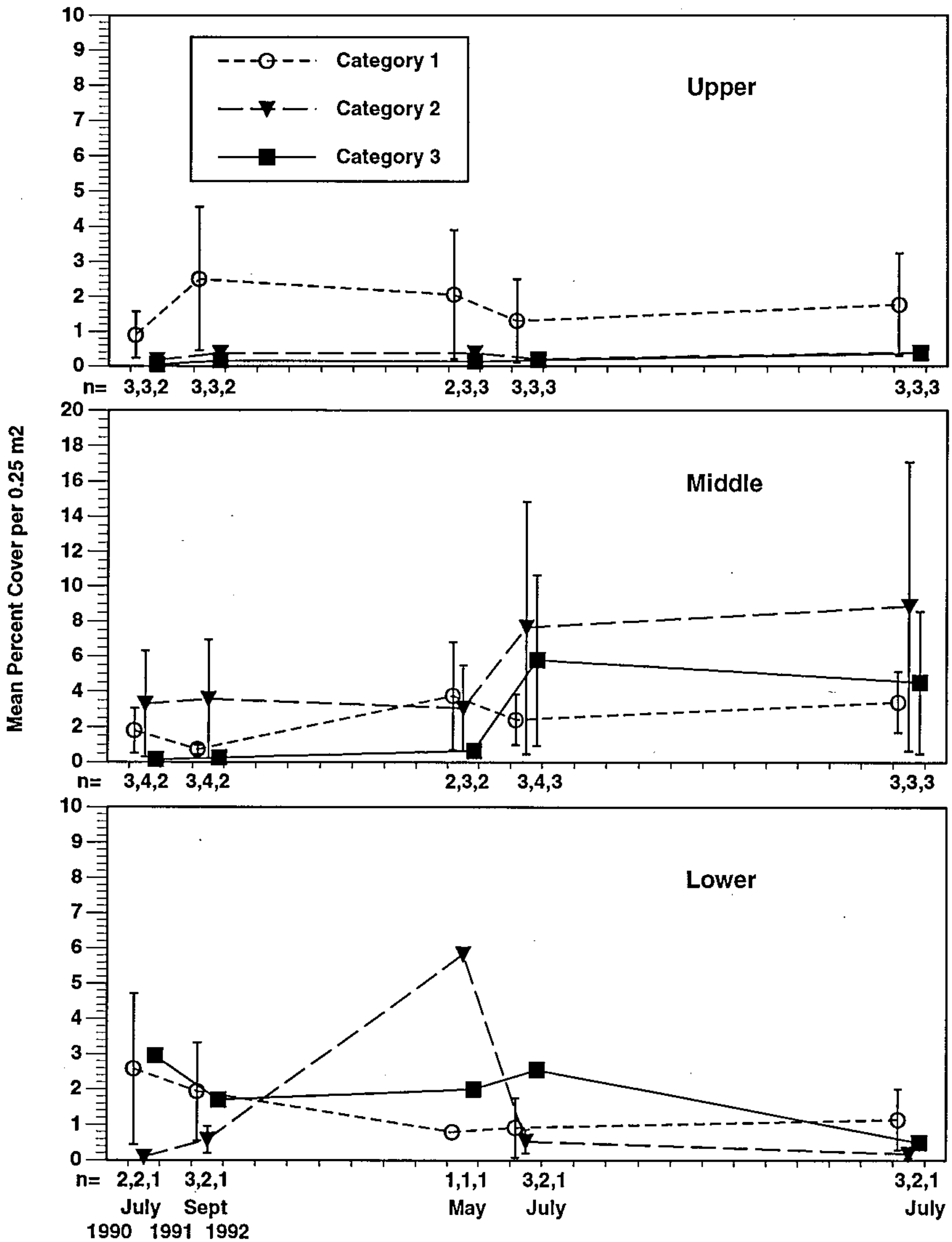

Figure 3-19. Mean percent cover (± 1 SE) of *Chthamalus dalli* from rocky sites, 1990–92. Number of stations sampled (n) shown below axis. Note change of scale in middle.

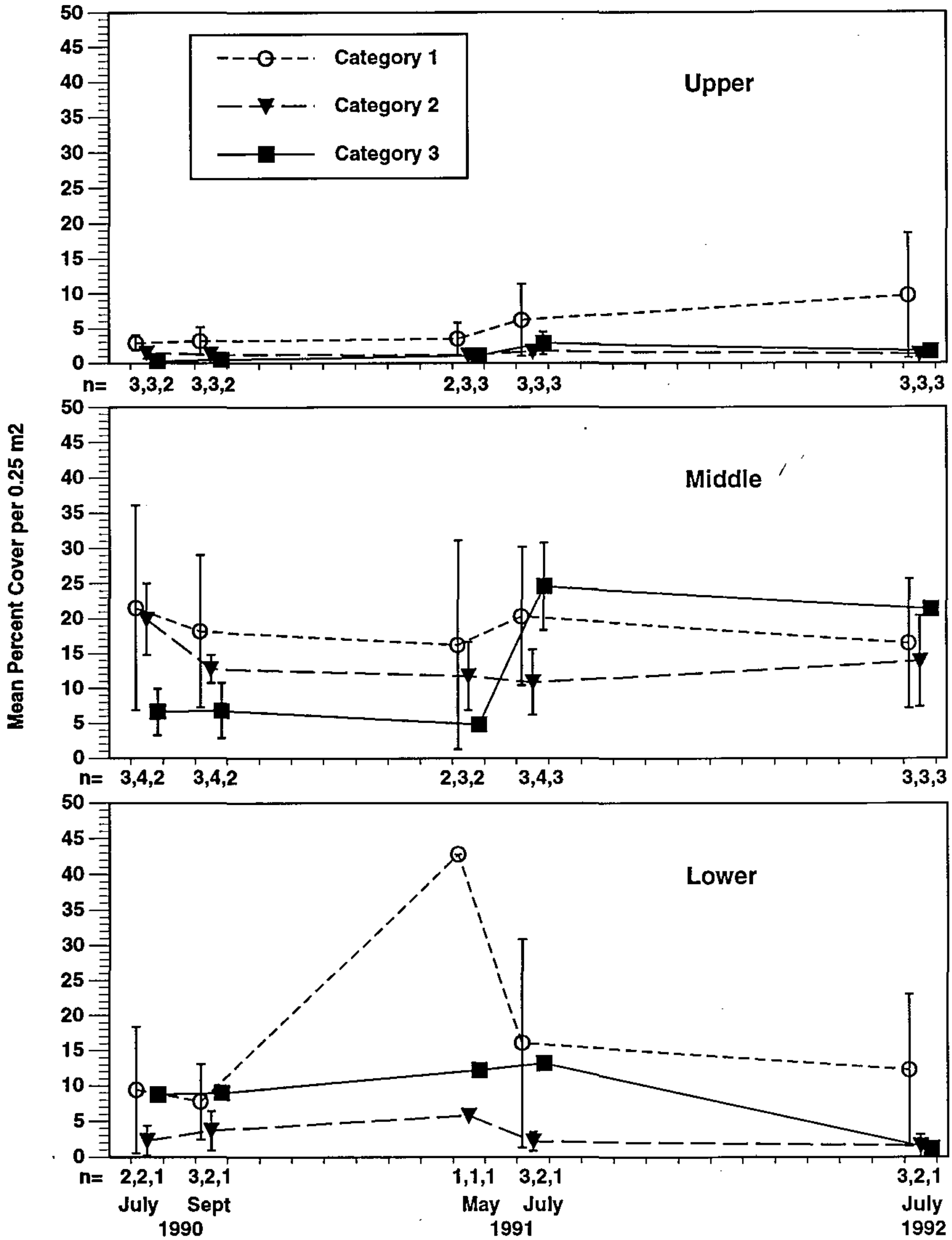

Figure 3-20. Mean percent cover (± 1 SE) of *Balanomorpha* from rocky sites, 1990–92. Number of stations sampled (n) shown below axis.

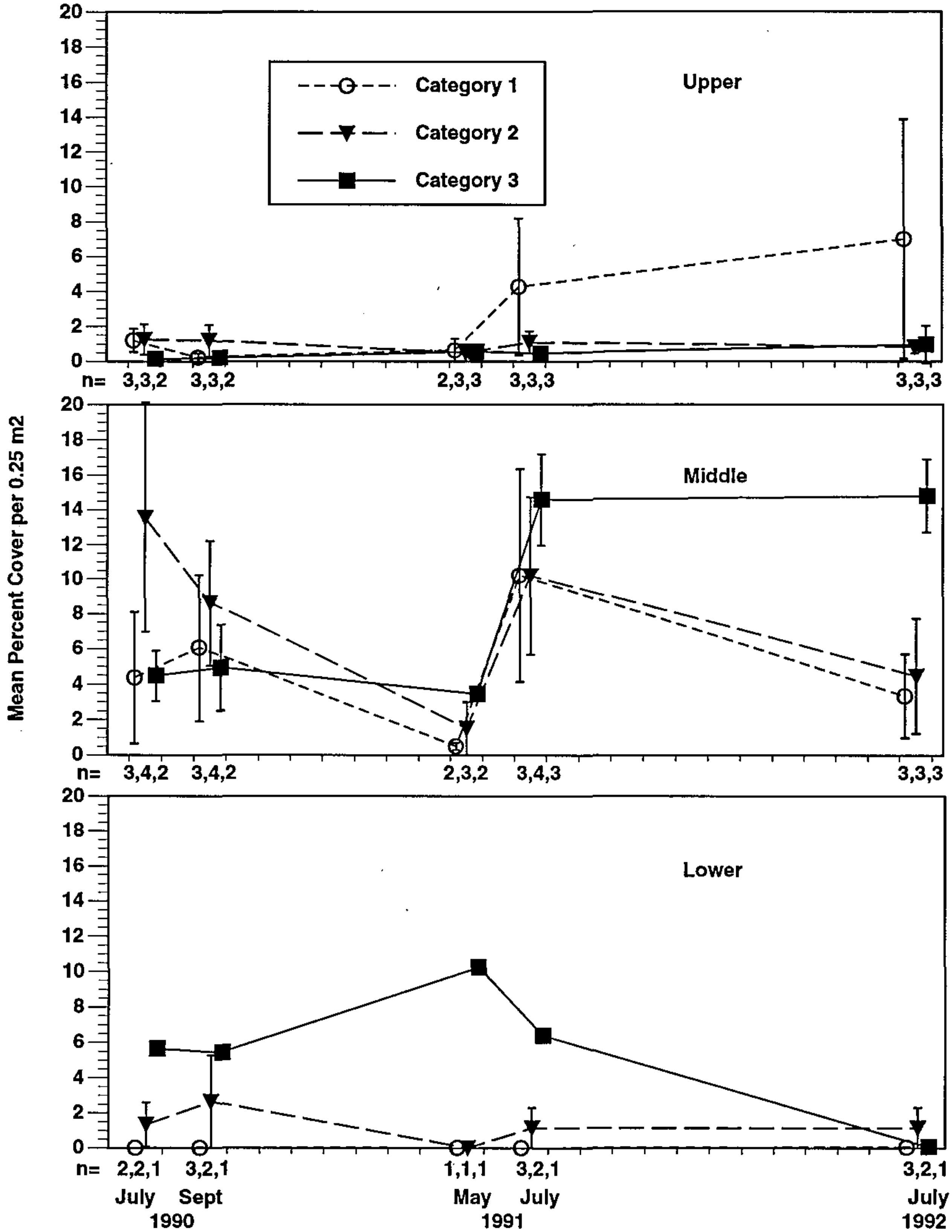

Figure 3-21. Mean abundance (± 1 SE) of *Semibalanus balanoides* from rocky sites, 1990–92. Number of stations sampled (n) shown below axis.

Barnacle recruitment is known to vary greatly between years and is dependent on larval availability, settlement rates, and early mortality of recruits (e.g., Bertness et al., 1992). An expected rise in numbers of barnacles colonizing open space at the Category 3 sites occurred in July 1991 at the middle elevation (primarily *S. balanoides*) but only to numbers already seen at the Category 1 sites. This trend was also seen at Sullom Voe by Rolan and Gallagher (1991). If succession occurs as expected on Category 3 sites (i.e., to convergence with conditions at Category 1 sites), we would expect *S. balanoides* to remain sparse at the lower stations and to be partially replaced at middle stations by *Balanus glandula* (Figure 3-22). In other temperate areas succession leads to gradual replacement by *Fucus* and *Endocladia* (Farrell, 1991). The absence of barnacle predators such as *Nucella* from the Category 3 sites may temper the normal succession pattern, however, and prolong the dominance of *S. balanoides*.

Mussels

High-pressure hot-water-wash treatment in 1989 resulted in high mortalities of blue mussels (*Mytilus* cf. *trossulus*) (Lees et al., 1993). At the Northwest Bay Islet middle rocky station, percent cover for mussels went from 4.6 percent before treatment (May 1989) to 0.2 percent following treatment (September 1989; ERCE, 1990a, b) and remained below that level until July 1991. By July 1992 *Mytilus* cover (including spat) had increased to 2.6 percent (Appendix Table C-1-2).

Overall patterns of mussel abundance (Figure 3-23) are not striking; large fluctuations in abundance at Category 1 lower stations reflect normal patterns of recruitment and predation at lower intertidal elevations. Massive but very patchy recruitment of mussels occurred throughout the study area in the spring of 1992, possibly in response to warmer than normal water temperatures seen in this El Niño year. This recruitment was not reflected in sampling of rocky sites, however. At least one to two more years will be necessary for mussel cover at hot-water-washed beaches to recover to prespill densities.

Multivariate Analysis of Epifauna, 1990-92

NMDS analysis of epibiota data from middle rocky stations for 1990 through 1992 showed patterns essentially the same as those reported from 1991 (Houghton et al., 1993) except that some of the erratic movements previously reported converged and all stations have moved slightly up the Y-axis (Figure 3-24). The overall movement up the Y-axis indicates a general response to some unknown regionwide environmental parameter (perhaps warmer water temperature or milder spring weather in 1992).

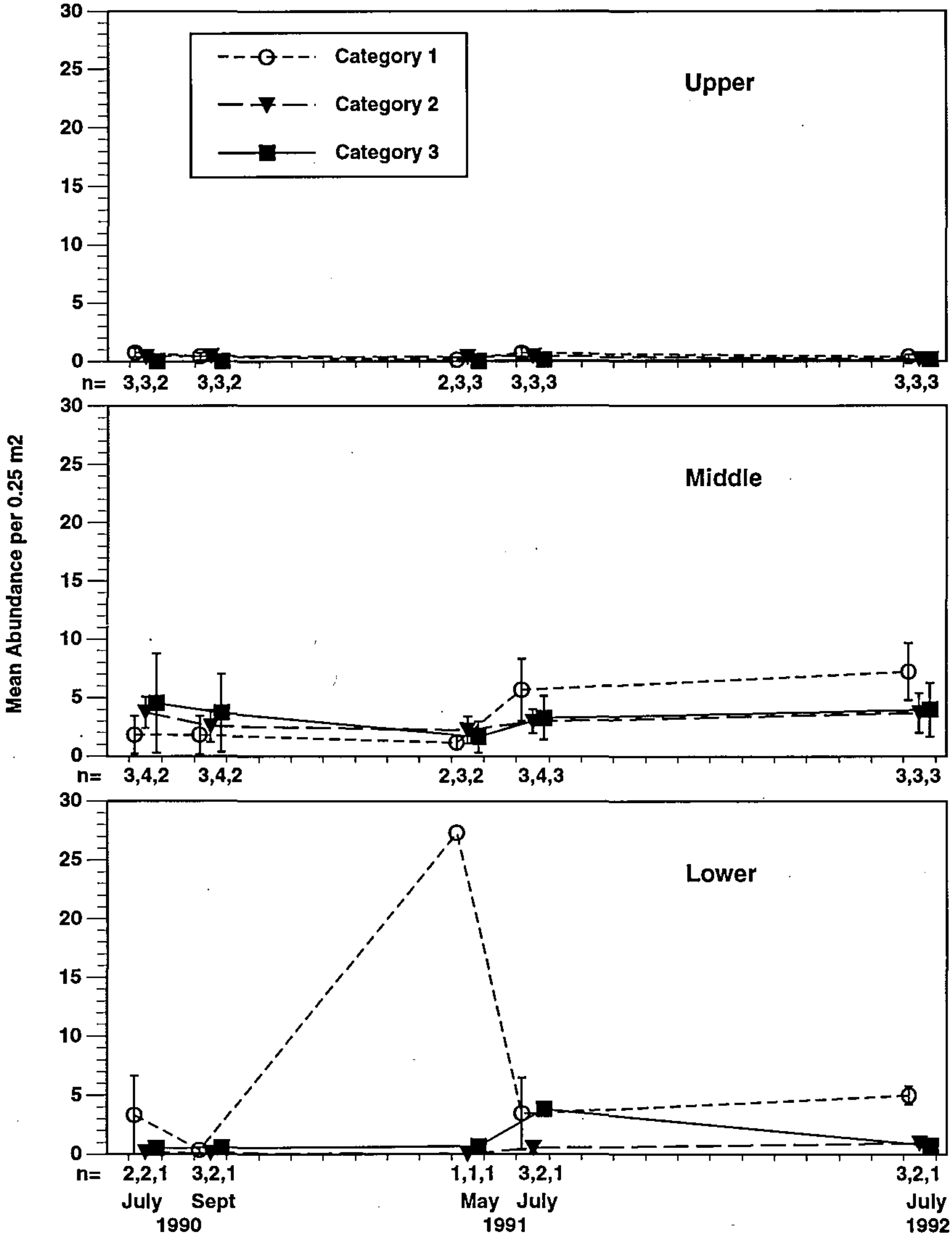

Figure 3-23. Mean abundance (± 1 SE) of mussels from rocky sites, 1990–92. Number of stations sampled (n) shown below axis.

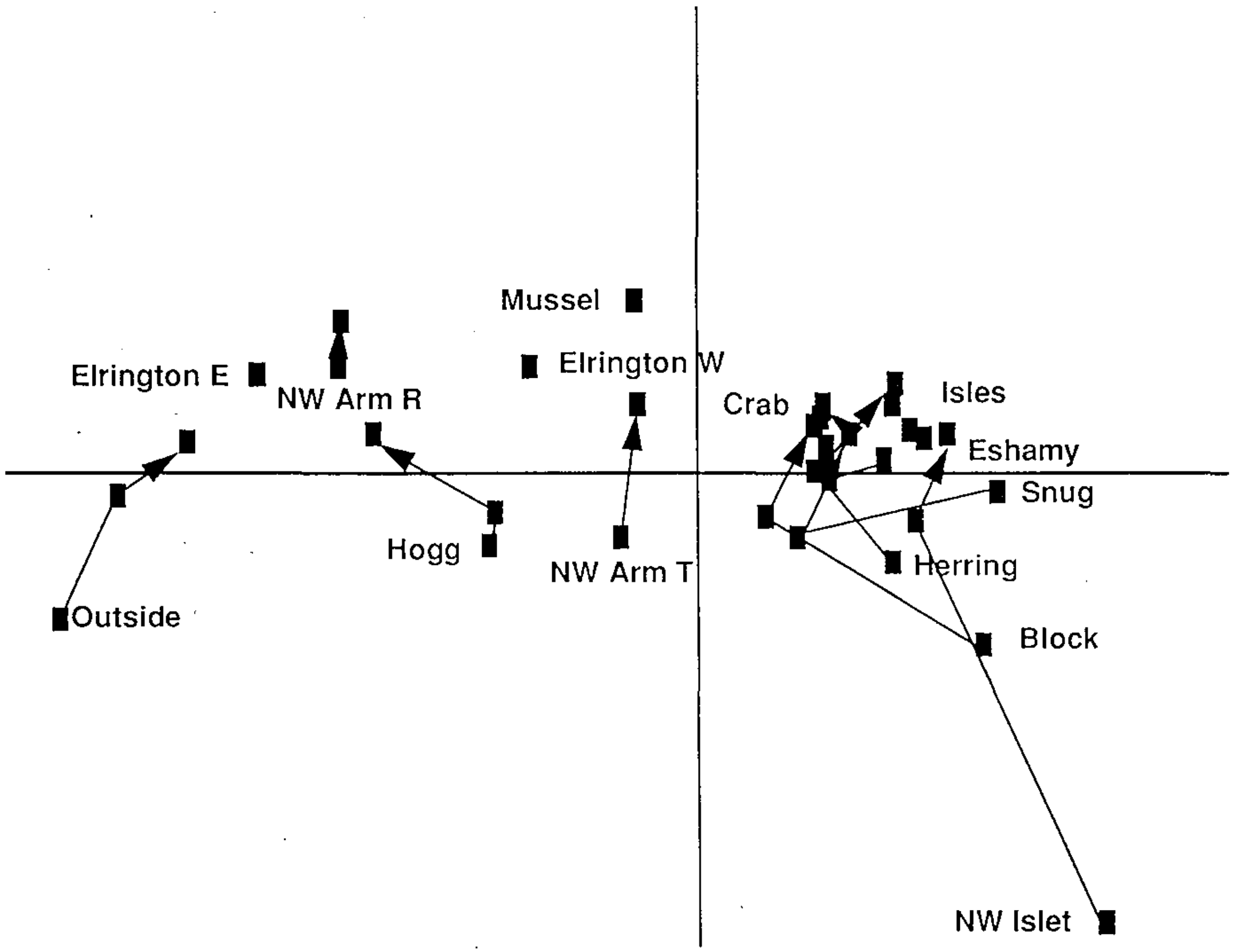

Figure 3-24. Principal component analyses of epibiota species abundance for all stations, 1990-92.

The Category 1 and 2 outlier sites on the left side of the 1991 graph (Hogg and Outside bays) are still relatively distant from the cluster but now are loosely joined by three new sites, Mussel Beach North and Elrington East and West, added in the 1992 survey. The appearance of these new sites outside the cluster suggests the sites previously identified as outliers are not unique; interestingly, these sites have substantially higher exposure indices than the sheltered cluster, ranging from 27 at Hogg Bay to 234 at Elrington Island (Hayes, 1992). Still outside the cluster, the Northwest Bay West Arm Category 3 site (exposure index 136) and its adjacent reference site (of unknown treatment) have converged slightly following a large shift up the Y-axis by the recovering Category 3 site.

Unlike PCA (Chapter 4), NMDS does not allow deep exploration of the variables that dictate the patterns shown. The use of mixed metrics (percent cover and count data) precludes calculating the usual survey indices (H', N, or biomass) so that species richness is the only useful index for correlations. Also, because the NMDS technique calculates ranked values to build the ordination, the ranking transformation eliminates the ability to directly correlate the results with environmental parameters.

Calculating a nonparametric rank correlation (Spearman's rho) between the ranks of the X-axis scores and species richness at each station yields a -0.43 correlation. This finding is supported by a mean species richness of 22.9 in the clustered group on the right side of the graph, compared to the mean of 31.9 species from stations left of the Y-axis. At the extreme left, the Category 2 station, Outside Bay, had the maximum of the data set, 40 species in 1992.

The trends over the last three years suggest that two groups may be forming from the middle rocky epibiota data. The right-side, species-poor (more sheltered) group (the tight cluster) shows no sign of diverging; the species-rich (more exposed) sites, Hogg and Outside bays, now show signs of converging. Next year's data should confirm or counter this trend. It also seems likely that the adjacent Northwest Bay West Arm treated site (Chapter 4) will make a radical turn toward the reference site in the coming years as it progresses toward full recovery.

Incorporating the 1989 data set will help establish starting points (in some cases, endpoints) for the yearly movements. A close examination of the species list from the four-year sequence should also establish the successional stages and patterns of recovery.

CHAPTER 4

INTERTIDAL INFAUNA

INTRODUCTION

Infauna (i.e., the animals living within the sediment) was sampled at middle and lower elevations in mixed gravel, sand, and/or mud (mixed-soft) sites. In June and July 1992, 13 lower-elevation stations and 7 middle-elevation stations were sampled. Eleven of the lower-elevation stations were analyzed, and samples from the remaining two lower stations and all of the middle-elevation samples were archived. Thus, all data presented in this chapter are from lower elevation stations. Detailed abundance data by taxon and station are provided in Appendix Tables D-1 and D-2.

METHODS

Field Methods

Infauna was sampled with five randomly located 0.009-m^2-by-15-cm-deep cores taken adjacent to the 0.25-m^2 quadrats used to sample epibiota (Chapter 3). A different position relative to the quadrat was sampled in each successive sampling trip to avoid resampling the same location.

All five cores were field-sieved through a 1.0-mm screen, and residue was preserved in a ten percent buffered formalin solution. A sixth sample was taken for grain size analysis, and a seventh sample was taken for TOC analysis and total Kjeldahl nitrogen. These samples were frozen whole until laboratory analysis.

Laboratory Methods

Samples were washed in the laboratory on a 0.5-mm screen to remove formalin and transferred to 70 percent ethanol. All animals were sorted from debris and identified to the lowest practicable taxon under a dissecting microscope. All sorting and taxonomy were done in the laboratories of Pentec Environmental, Inc. For quality control, ten percent of the samples were re-sorted. Problematic species were identified by regional specialists (Mr. Jeff Cordell, University of Washington, Seattle, Washington, Crustacea; Mr. Howard Jones, Marine Taxonomic Services, Corvallis, Oregon, Polychaeta; Mr. Allan Fukuyama, Pentec Environmental, Inc., Edmonds, Washington, Mollusca).

Grain Size, TOC, and Total Kjeldahl Nitrogen Analyses

Field-preserved whole sediment samples collected in June and July 1992 from 12 lower-elevation mixed-soft stations were analyzed for grain size following the procedures of McNeil and Ahnell (1964). Sediments were wet-sieved through a standard sequence of nine screen sizes (12.5-mm to silt-clay < 63 microns). Each fraction was then placed into displacement cylinders, and displaced water was measured in a graduated cylinder.

Sediment samples from 13 lower elevation stations were frozen in the field and sent to Analytical Resources, Inc. for TOC and total Kjeldahl nitrogen analyses. TOC analysis was done on a Dohrmann DC-180 Carbon Analyzer on samples that were dried (70°C), ground, then sieved (120-micron mesh). Calibration, standardization, and spiking were conducted following manufacturers' directions using potassium phthalate (KHP). Samples were purged of inorganic carbon prior to analysis. Total Kjeldahl nitrogen analysis was done using methods as referenced by Plumb (1981).

Data Management and Statistical Analyses

Summary of Taxon Deletions and Consolidations Employed for Analysis of the Infaunal Data

To produce tables for consistent analysis and comparison with previous surveys, the primary (raw) infaunal database (Appendix Table D-1) was revised considerably. The first step in the revision was to delete irrelevant taxa that are typically epifaunal; these included bryozoans and other taxa (e.g., *Nucella lima, Pagurus* spp., *Turtonia minuta,* or chinonomid and muscid flies and larvae) that, although sampled and in some cases very abundant, are not truly infauna. The next step was to consolidate taxon designations that were recorded distinctly but that we have solid reasons to believe represent a single species and to eliminate ambiguous taxa (i.e., generic or family designations for which more than one species occurs in Prince William Sound). The third step was to delete meiofaunal taxa, including oligochaetes, harpacticoid copepods, nematodes, and nemerteans, that are not adequately sampled by the techniques employed in this study. Calculation of total abundance (N) of selected macroinfaunal organisms (those consistently retained on a 1.0-mm screen) was made on this data set (Appendix Table D-2) and used in subsequent analyses. This data set was also used for species richness (S) and species diversity (H') calculations presented in Tables 4-1 and 4-2 and all subsequent statistical analyses. Taxa deleted from the primary database (Appendix Table D-1) for these calculations and production of data summary tables are listed at the end of Appendix Table D-2. Although not included in calculation of assemblage attributes (N, S, H'), data on meiofaunal groups are presented separately for discussion purposes.

Inferential Statistics

Various statistical analyses were applied to quantitatively describe the data (number of species, number of individuals, cover, species diversity, evenness) and evaluate the significance of the findings. Parametric and nonparametric tests were applied as appropriate to evaluate the significance of differences observed between station categories. In these tests, the mean of all subsample (replicates) at a given station was used to represent each variable; thus, n = the number of stations within that category where the variable in question was measured. Chapter 3 provides additional statistical approaches. Some trends are noted as differences in mean values where no probability value is given. These differences are considered biologically relevant even though they are not statistically significant because of the limited replication of stations within site categories.

Table 4-1. Statistics for numerical infaunal community attributes by treatment category, Prince William Sound, 1992.

		Statistic	Number of Individuals	Number of Taxa	H'	J
Category						
	Bainbridge Bight	Average/core	38.4	7.4	1.63	1.87
		SD	17.0	1.5	0.37	0.27
		Overall	192.0	11.0	2.06	1.98
	Crab Bay	Average/core	98.2	10.4	1.73	1.75
		SD	86.9	3.4	0.21	0.27
		Overall	491.0	23.0	1.98	1.45
	Outside Bay	Average/core	181.6	20.8	2.10	1.59
		SD	67.6	2.7	0.28	0.17
		Overall	908.0	43.0	2.43	1.49
	Sheep Bay	Average/core	81.8	16.0	2.21	1.84
		SD	34.3	3.2	0.17	0.13
		Overall	409.0	35.0	2.67	1.73
	All Sites	Average/core	100.0	13.7	1.92	1.76
		SD	60.0	6.0	0.28	0.13
		Overall	500.0	28.0	2.29	1.66
Category 2						
	Block Island	Average/core	95.8	15.2	2.14	1.86
		SD	71.4	6.9	0.45	0.15
		Overall	479.0	32.0	2.75	1.83
	Herring Bay	Average/core	332.0	18.2	1.76	1.40
		SD	51.3	2.6	0.44	0.35
		Overall	1660.0	32.0	2.10	1.39
	Mussel Beach	Average/core	87.5	14.0	2.09	1.85
		SD	55.8	5.1	0.45	0.17
		Overall	438.0	34.0	2.77	1.81
	Snug Harbor	Average/core	113.8	9.8	1.72	1.74
		SD	46.6	0.8	0.13	0.11
		Overall	569.0	18.0	2.07	1.65
	All Sites	Average/core	157.3	14.3	1.93	1.71
		SD	117.0	3.5	0.22	0.22
		Overall	786.5	29.0	2.42	1.67
Category 3						
	Northwest Bay West Arm	Average/core	22.6	7.4	1.56	1.89
		SD	17.0	2.7	0.26	0.35
		Overall	113.0	16.0	1.89	1.57
	Shelter Bay	Average/core	18.2	4.0	1.04	1.85
		SD	13.5	1.6	0.42	0.46
		Overall	91.0	13.0	1.34	1.20
	Sleepy Bay	Average/core	52.0	7.2	1.42	1.78
		SD	43.8	3.3	0.50	0.41
		Overall	260.0	18.0	1.95	1.55
	All Sites	Average/core	30.9	6.2	1.34	1.84
		SD	18.4	1.9	0.27	0.06
		Overall	154.7	15.7	1.73	1.44

Table 4-2. Intertidal macro-infaunal abundance (no./0.009 square m) from lower mixed-soft stations, July 1992. (*=p<0.10;**=p<0.05)

	Category 1		Category 2		Category 3		Randomization	Multiple Comparison Randomization t-tests, 2-tailed		
Lumped Taxa	Mean	SD	Mean	SD	Mean	SD	ANOVA	1 vs. 2	1 vs. 3	2 vs. 3
Nemertea	4.00	3.66	20.85	31.63	3.87	1.63				
Nematoda	15.45	16.65	87.55	66.63	19.73	19.40	*	**		
Oligochaeta	30.80	35.88	35.20	19.22	6.93	10.97				*
Polychaeta	20.20	13.53	31.25	12.46	11.67	7.86				
Gastropoda	30.05	29.84	66.75	108.66	4.20	3.12				
Bivalvia	27.30	29.31	24.60	18.12	0.73	0.12				**
Crustacea [1]	21.60	21.99	34.15	29.68	14.33	12.90				
Harpacticoida	7.50	10.23	50.85	60.14	0.13	0.12				
Sipunculida	0.00	0.00	0.35	0.70	0.00	0.00				
Echinodermata	0.65	1.30	0.55	0.68	0.00	0.00				
Without Harpacticoida, Nematoda, & Oligochaeta										
Diversity (H')	1.92	0.28	1.93	0.22	1.34	0.27	**		*	**
Abundance (N)	99.80	60.01	157.65	116.70	30.93	18.38				*
Number of Taxa (S)	13.65	5.95	14.30	3.48	6.20	1.91	*			*
Number of Stations	4		4		3		4,4,3	4,4	4,3	4,3

1. Crustacea does not include Harpacticoida

Randomization Tests

Infauna were lumped into major taxonomic groups (e.g., Polychaeta, Bivalvia, etc.) for randomization tests of each taxonomic group to determine significant category effects (ANOVA) and differences between treatment categories (t-tests). Similar procedures were used (without lumping) to compare total abundance, number of taxa, and diversity (Shannon H'). Only 2-tailed test results were considered under the assumption that, depending on the taxon, either increases or decreases could occur with oiling or with treatment. Reformulating null hypotheses as a 1-tailed test (e.g., "oiling does not decrease abundance of mollusks") would increase the number of significant effects found. Because direction of change varied among taxa, however, this was not done. The randomization routines were adapted from algorithms published by Edgington (1987).

Cluster Analysis

Cluster analysis was used for comparison of infauna species composition among stations. The analysis used the Canberra metric measure of dissimilarity and the flexible sorting strategy (Clifford and Stephenson, 1975) to evaluate the site-taxon matrix reduced to the most abundant 50 taxa from the list of selected macroinfauna. The purpose of reducing the matrix to 50 taxa was to eliminate as much random variation (noise) from the data set as possible. The infaunal matrix was reduced initially on the basis of abundance (single occurrences were eliminated). The next level of reduction was based on frequency of occurrence; taxa that occurred at only one site were eliminated except where a group of abundant taxa appeared to characterize a site. The final level of reduction was based on examination of a preliminary version of the nodal table for sites and taxa; taxa observed at two or more sites but not more than once in at least one site group were deleted. Taxa that were abundant at a single site were not deleted in order to preserve the distinctive faunal character of the site.

Principal Components Analysis

PCA is a multivariate ordination technique. The objective of the technique is to reduce a multivariate data set into a few new, uncorrelated, component variables expressed as vectors. Each vector is actually an equation describing a line through the multidimensional data cloud; each line is perpendicular (uncorrelated) to the previous lines until the total variance of the data cloud has been accounted for (usually three to eight components from these data sets). The resulting component vectors are then examined to discern which species are most heavily weighted (most important) in the vector, how well the component accounts for the variance of each species, and how closely each species correlates with the component. The lists of dominant species for each significant component are then interpreted for biological meaning.

As in any other multivariate technique, the rare or sparsely distributed species are removed from the initial analysis to reduce the noise in the system. The remaining abundances then are log transformed to reduce population scaling effects. Polyspecific groups are usually discarded to avoid distorting the discrimination between sites.

The resulting component scores are plotted on three-dimensional axes and examined for significant site clustering, which indicates site similarities, and for trends in movement between years, which indicate possible trends in successional recovery. The dominant species from each significant component were extracted as suggested key indicator species for future monitoring.

To further understand the resulting patterns, the station scores were correlated against various parameters including PAH concentrations, biological indices, sediment grain distribution, and treatment categories. When it became apparent that there were two station groupings represented in the results, two additional PCAs were run to examine the groupings more closely. Various group parameters were correlated and compared for significance between groups using t-tests.

The data set was also examined using detrended correspondence analyses to confirm the validity of the PCA analyses. The CANOCO computer package (Ter Braak and Prentice, 1988) was used for all multivariate analyses.

For each of the multivariate techniques, determining which component axes were significant contributors to the final ordination was based on the SCREE[1] diagram technique. In this technique the percent variance accounted for by each axis is plotted as a simple line graph. The axis at which the line first breaks or begins to plateau is considered the least significant axis to include in the interpretation. Typically, no more than two or three axes were significant throughout this study.

RESULTS

Sediment Quality

Grain size analyses were done on Category 1, Category 2, and Category 3 lower mixed-soft stations (n = 4 for each category) from frozen samples collected in June and July. Volume displacement data for nine size fractions at each station are provided in Appendix Table A-5. In a randomization ANOVA there were no statistically significant differences among the three categories for the fines, sand, or coarse fractions. Cobbles and larger pebbles (> 12.5 mm) were most prevalent at Category 2 and Category 3 sites. Coarse sand fractions (granules and smaller pebbles of 0.5 and 1.0 mm) were most abundant at Category 1; Category 2 and Category 3 coarse fractions were about the same (Figure 4-1).

The percent fines (all fractions 0.125 mm or finer) was lowest at Category 3 lower stations; there was a significant difference between Category 1 and Category 3 (randomization t-test, $0.05 < p < 0.10$). This pattern was attributed to the high proportions of silt/clay at the Category 1 stations at Crab Bay and Bainbridge Bight and the Category 2 station at Herring Bay along with the low proportions of silt/clay at the Category 3 stations at Northwest Bay West Arm and Sleepy Bay (Appendix Table A-5). The silt/clay fraction ranged from 0.9 percent at Sleepy Bay to 16.5 percent at Herring Bay. Average silt/clay content at Category 1, 2, and 3 lower stations was 12.0 +/-3.1, 8.8 +/- 5.3, and 3.3 +/-3.0 percent, respectively.

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1 The name "SCREE," according to Jackson (1991), is derived from the definition of scree as the rubble at the base of a cliff. In this analogy, retained roots represent the cliff, and the deleted ones are the rubble.

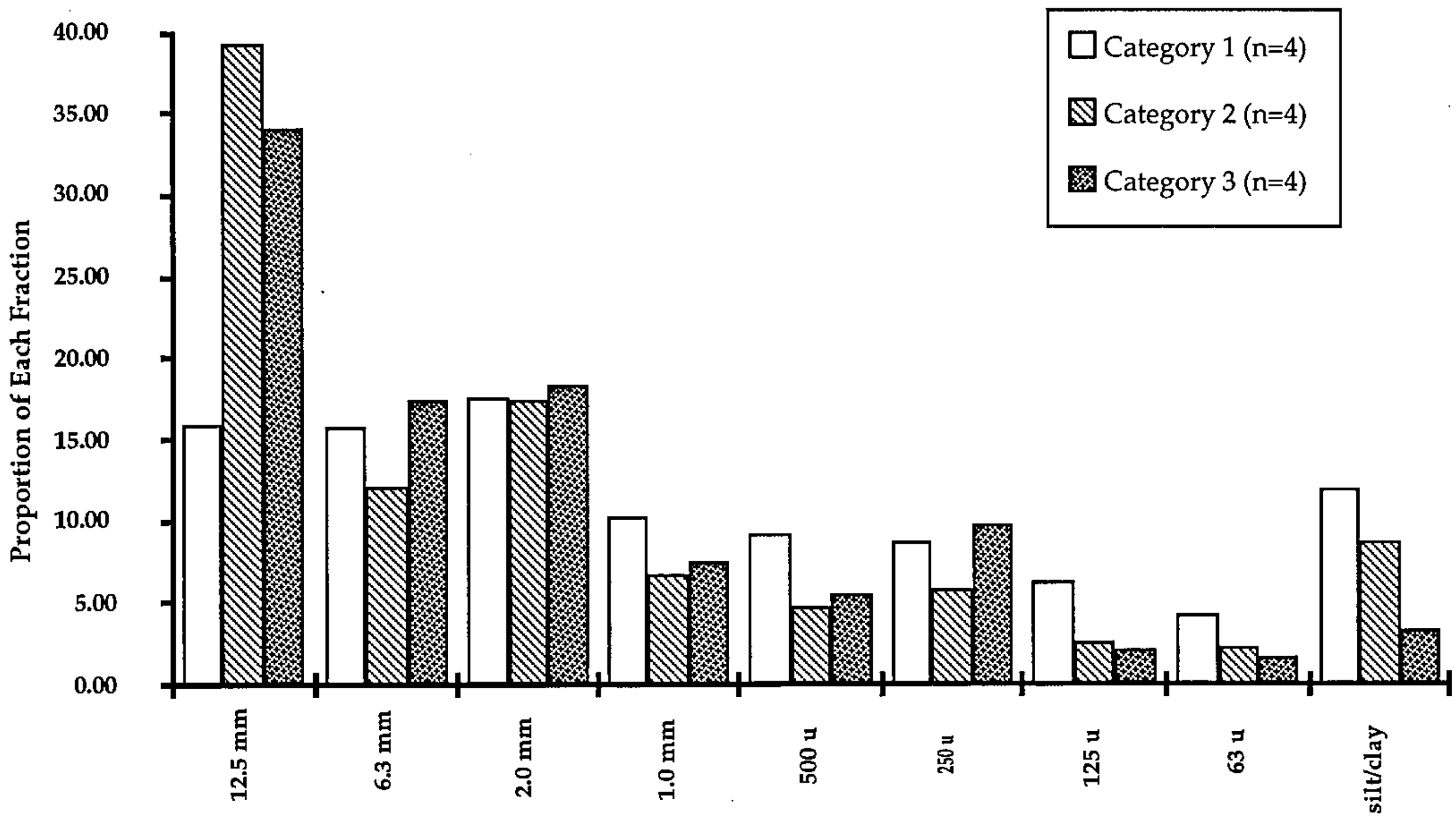

Figure 4-1. Grain size analysis of lower mixed-soft stations by category, July 1992.

TOC and total Kjeldahl nitrogen were analyzed from four Category 1, five Category 2, and four Category 3 lower stations. Mean TOC was highest at Category 2 sites with a value of 33,104 ppm; the lowest mean value was found at Category 3 sites at 8,675 ppm (Appendix Table A-6). Snug Harbor and Ingot Island, both Category 2, had the highest TOC; the Category 3 Shelter Bay station was lowest at 6,120 ppm. Highest mean total Kjeldahl nitrogen was also at Category 2 lower stations (703 ppm), and Category 3 stations were again lowest (146 ppm). Snug Harbor had the highest value for total Kjeldahl nitrogen (2,190 ppm), and Northwest Bay West Arm (Category 3) had the lowest value (56 ppm).

Infaunal Communities

General Abundance of Major Infaunal Taxa

On the basis of abundance, the total infaunal component (including meiofauna) of the samples from lower mixed-soft stations was dominated by nematodes. Next, in order of decreasing abundance were gastropods, oligochaetes, crustaceans (excluding harpacticoids), and polychaetes (Table 4-2). On average all taxa but bivalves were more abundant at Category 2 sites than elsewhere (Figure 4-2).

Several of the major taxa in the infaunal component are largely meiofaunal (i.e., quite small). Because meiofaunal taxa are inconsistently sampled with a 1-mm sieve and are influenced by the quantity of organic debris in the sample, they have been excluded from the quantitative analyses below.

Patterns in Community Attributes

Community attributes are presented for individual cores, averages for all cores from a site, and for the pooled (composited) species lists for a site. Data for each of these approaches are presented because they provide information on different spatial scales for a site. Data for the individual cores indicate conditions on a scale of 0.009 m^2, and the averages and associated standard deviations (SD) describe variability on that scale. The pooled species data provide a good estimate of the overall (site-wide) condition of the infauna at a site with regard to abundance, species richness, and species diversity. Comparison of the patterns exhibited by the infaunal attributes resulting from these different summation methods provides insight into the effects of (spatial) scale.

A total of 5,610 specimens consisting of 85 macroinfaunal taxa was identified in infaunal samples collected in Prince William Sound in July 1992 (Appendix Tables D-2 and D-3). Abundance varied substantially among cores at many sites and among sites. Number of specimens (N) in cores spanned nearly two orders of magnitude and ranged from 6 (Northwest Bay West Arm) to 429 (Herring Bay). There was no category effect in an ANOVA ($p > 0.1$), but in paired t-tests the mean number of infaunal organisms/core at Category 2 lower stations was significantly greater than at Category 3 lower stations ($p < 0.1$; Table 4-2). By site, the average number of specimens/core varied by more than an order of magnitude and ranged from 17.8 (Shelter Bay; Table 4-1) to 355.8 (Herring Bay). These data suggest that, though small-scale (per core) abundance was lowest at Northwest Bay West Arm, density was lower at Shelter Bay on a site-wide (cumulative) basis (both sites are Category 3). Small-scale and site-wide density were both highest at Herring Bay (Category 2).

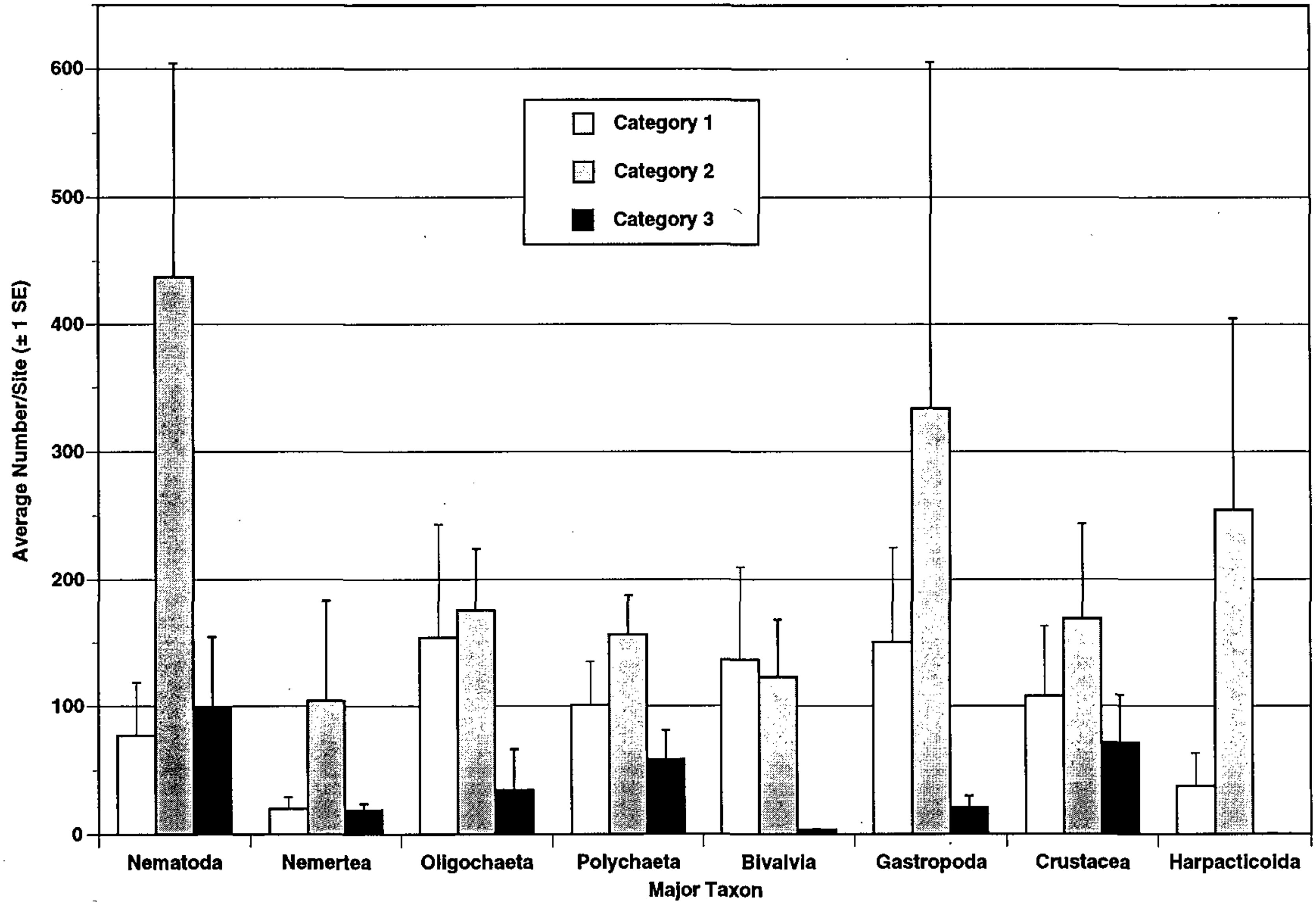

Figure 4-2. Infaunal abundances of major taxa from lower intertidal stations, July 1992.

Number of taxa (S), tabulated on the basis of individual cores and the pooled species list for each site, varied substantially among cores at many sites and among sites and site categories (randomization ANOVA, $p < 0.1$; Table 4-2). Average number of species/core ranged from 4.0 (Shelter Bay) to 20.8 (Outside Bay), and total taxa/site ranged from 11 (Bainbridge Bight) to 43 (Outside Bay; both Category 1; Table 4-1). These data suggest that, on the smaller scales, infaunal species richness was lowest at Shelter Bay, but that on a site-wide basis, the infaunal assemblage was richer (contained more species) at Shelter Bay (Category 3) than at Bainbridge Bight (Category 1). In paired t-tests the number of taxa at Category 2 lower stations was significantly greater than at Category 3 lower stations ($p < 0.1$; Table 4-2). The infauna at Outside Bay (Category 1) was richest on all scales.

Species diversity (H') of selected macroinvertebrates, calculated for individual core samples and the pooled species list for each site, also varied substantially. H' for individual core samples ranged from 0.55 (Shelter Bay) to 2.68 (Mussel Beach; Appendix Table D-2). Based on individual cores, mean H' averaged from 1.04 (Shelter Bay; Table 2) to 2.21 (Sheep Bay) and, based on the pooled species lists for each site, from 1.34 (Shelter Bay) to 2.77 (Mussel Beach; Table 4-1). These data suggest that, on all scales, the infauna at Shelter Bay was the least diverse. In contrast, the infauna at Mussel Beach (Category 2) had the highest individual and site-wide diversity, and Sheep Bay (Category 1) had the highest average diversity. Species diversity varied significantly among treatment categories (ANOVA $p < 0.05$), and in paired t-tests, both Category 1 and 2 sites had significantly greater diversity than did Category 3 sites ($p < 0.1$ and < 0.05, respectively; Table 4-2).

The assemblage attributes were strongly correlated. Species diversity (H') was positively correlated (Pearson Product Moment) with number of organisms (N) and taxa (S) ($r = 0.63$, $p < 0.05$; $r = 0.90$, $p < 0.001$, respectively). N and S were strongly correlated as well ($r = 0.87$, $p < 0.001$).

In summary, treatment category averages for these community attributes were invariably highest in Category 2 and lowest in Category 3 (Tables 4-1 and 4-2). Abundance averaged three to four times higher; numbers of taxa were about twice as high; and species diversity was about 40 percent higher at Category 1 and 2 sites than at Category 3 sites.

Patterns in Distribution of Selected Major Infaunal Taxa

The major macroinfaunal taxa used in quantitative analyses were Anthozoa, Polychaeta, Sipunculida, Phoronida, Bivalvia, Gastropoda, Crustacea, and Echinodermata. Among these, only polychaetes, bivalves, gastropods, and crustaceans were common; abundances of the remaining taxa were several orders of magnitude lower (Table 4-2). Taxa that are primarily meiofaunal have been excluded.

General distribution patterns for these major taxa appear to be related to type of treatment received. Average density of all major taxa was highest in Categories 1 and 2 and lowest in Category 3 (Table 4-2; Figure 4-2). Variability within the categories was high, however. Gastropods were the most abundant taxon in Categories 1 and 2, where they averaged 30 and 42 percent, respectively, of the total number of macroinfaunal component; in Category 3, they made up only 14 percent of that component. Bivalves contributed 27 and 16 percent of that component in Categories 1 and 2 but only 3 percent in Category 3. In a paired t-test, bivalves were significantly more abundant in Category 2 sites than in Category 3 ($p < 0.05$; Table 4-2).

Polychaetes and crustaceans contributed about 20 percent each in both Categories 1 and 2 but substantially more (37 and 46 percent) in Category 3. Average abundance of all major taxa was considerably lower at Category 3 sites than in the other categories (Figure 4-2). If one assumes that Category 1 represents the undisturbed condition and Categories 2 and 3 represent stages in recovery, these relationships suggest that the infaunal populations at Category 2 sites have nearly recovered and those at Category 3 sites have been severely disturbed but are recovering. Crustaceans and polychaetes appear to be recovering more rapidly than gastropods or bivalves; of these taxa the bivalves appear to be recovering most slowly (see discussion of venerid clams in Chapter 5).

Community Dominants

Based on ranked species lists (Table 4-3), numerically dominant taxa at Category 1 and 2 sites varied considerably from those at Category 3 sites. Four taxa were among the ten most abundant in all three categories (the gastropod *Fartulum* sp., the cumacean *Cumella vulgaris*, the snail *Alvania compacta*, and the polychaete *Pholoe minuta*). As indicated above, bivalves and gastropods were strong dominants at Category 1 and 2 sites, whereas crustaceans and polychaetes dominated at Category 3 sites. Among the ten most abundant taxa at Category 1 and 2 sites were the bivalve *Mysella tumida*, and the gastropods *Cingula* sp. 1, *Fartulum* sp., and *Alvania compacta* (Table 4-3). *Alvania* and *Fartulum* were also among the most abundant ten taxa at Category 3 sites, but generally that category was dominated by crustaceans (*Paramoera* sp. 2, *Spinulogammarus subcarinatus*, and *Pontogeneia ivanovi*) and polychaetes (*Saccocirrus eroticus*, *Eteone spetsbergensis*, and *Nereis vexillosa*) that were uncommon or absent at Category 1 and 2 sites.

The meaning of the dominance described for each category is weakened by the fact that some of the dominant taxa occurred at only a single site (two, three, and four taxa in Categories 1, 2, and 3, respectively; Appendix Table D-3). If these taxa are eliminated from this list of dominant taxa in the treatment categories because they are not generally representative of the infauna, however, the pattern of dominance by clams and snails in Categories 1 and 2 and polychaetes and crustaceans in Category 3 is unchanged. It appears that dominance by polychaetes and gammarid amphipods indicates disturbance or early stages of succession, whereas dominance by clams and gastropods is more indicative of stability.

Site and Taxon Groupings

When infaunal taxa were aggregated on the basis of similarity (Canberra metric measure of dissimilarity and group-averaging sorting strategy) in their 1992 distribution among sampling sites, they segregated into two major site groups and one poorly related site. The two major site groups segregated largely along the divisions of treatment categories, but the strength of the relationship was generally weak. Site Group A was dominated by and included all of the Category 1 sites. It also included two Category 2 sites; a Category 3 site (Sleepy Bay) was poorly related and is considered an outlier. Site Group B included two sites each from Categories 2 and 3, which formed Site Groups B1 and B2, respectively.

Table 4-3 Comparison of 10 most abundant infaunal taxa within treatment categories* and overall in Prince William Sound study sites, July 1992.

Overall			Category 1			Category 2			Category 3		
Taxon	Ave. No.	Rank	Taxon	Ave. No.	Rank	Taxon	Ave. No.	Rank	Taxon	Ave. No.	Rank
Rissoidae	12.82		Mysella tumida	17.70	1	Rissoidae	33.90	1	Paramoera sp. 2	6.67	1
Cingula sp. 1	11.85		Cingula sp. 1	16.15	2	Cingula sp. 1	16.40	2	Saccocirrus eroticus	5.13	2
Mysella tumida	10.58		Fartulum	7.10	3	Cumella vulgaris	15.80	3	Spinulogammarus subcarinatus	4.53	3
Cumella vulgaris	7.84		Ampithoe dalli	5.20	4	Mysella tumida	11.05	4	Pholoe minuta	3.80	4
Fartulum	5.67		Cumella vulgaris	5.20	5	Fartulum	8.00	5	Alvania compacta	2.80	5
Alvania compacta	4.80		Protothaca staminea	4.55	6	Alvania compacta	6.75	6	Pontogeneia ivanovi	1.53	6
Pholoe minuta	4.47		Alvania compacta	4.35	7	Pholoe minuta	6.65	7	Cumella vulgaris	0.73	7
Protothaca staminea	3.78		Corophium brevis	2.95	8	Eteone longa	6.20	8	Fartulum	0.67	8
Corophium brevis	3.11		Pholoe minuta	2.80	9	Ampithoe kussakina	6.10	9	Eteone spetsbergensis	0.60	9
Eteone longa	3.00		Macoma balthica	2.50	10	Cingula sp. 2	6.05	10	Nereis vexillosa	0.60	10
			Eteone longa	1.80	13	Protothaca staminea	5.65	11	Mysella tumida	0.47	12
			Ampithoe kussakina	1.55	15	Corophium brevis	5.60	12	Eteone longa	0.33	14
			Rissoidae	1.30	16	Macoma balthica	2.75	15	Protothaca staminea	0.27	15
			Paramoera sp. 2	1.05	18	Nereis vexillosa	0.50	30	Ampithoe kussakina	0.20	17
			Nereis vexillosa	0.65	24	Eteone spetsbergensis	0.35	34	Cingula sp. 1	0.07	21
			Eteone spetsbergensis	0.15	31				Rissoidae	0.07	21

* Abundance and rank of taxa occurring in top ten at any site are indicated for each category if they occur.
Absence of a taxon from the list for a category indicates that it was not found at those sites.

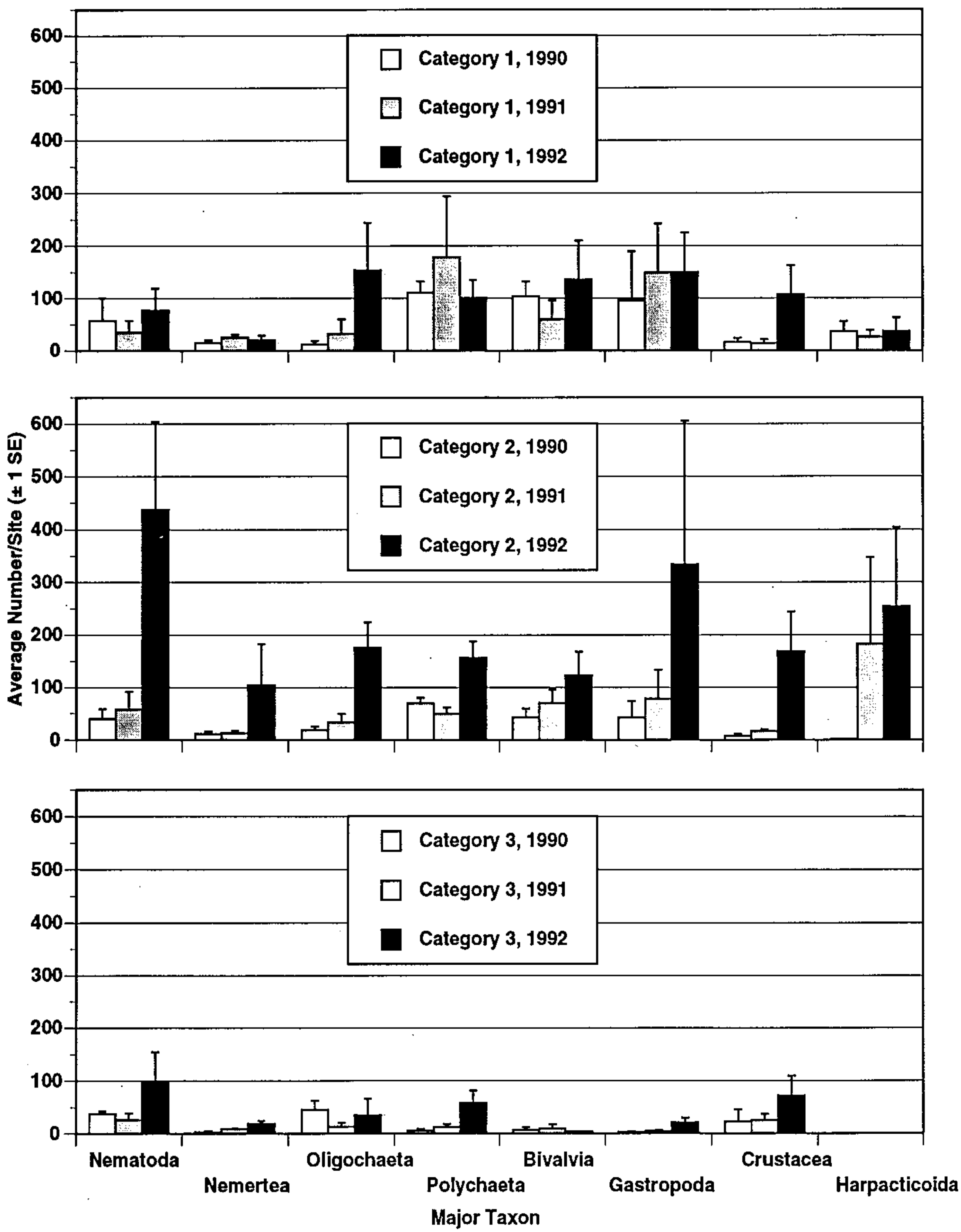

Figure 4-3. Infauna abundances of major taxon from lower intertidal stations, 1990-92.

The taxa segregated into six fairly distinct subgroups within two major groups. Examination of density and occurrence patterns in the nodal table (Table 4-4) reveals that Species Group I included mainly widely distributed and relatively common taxa. Mollusks, with 60 percent of the taxa, dominated Species Group I. The most abundant polychaetes and crustaceans formed the remainder of the group. These taxa appear to comprise the community dominants (Table 4-4). While the group included only about 20 percent of the taxa examined in this matrix, average abundance of its taxa was generally several times higher than in Species Group II (Table 4-5). The latter group generally comprised less widely distributed taxa that occurred at lower densities. It was dominated by polychaetes with gammarid amphipods, the next most common taxon.

DISCUSSION

Infaunal Assemblages

The 1992 infaunal data from lower mixed-soft stations continue to exhibit a strong pattern of dissimilarity between Category 1 and 2 sites, which support higher numbers of organisms, more taxa, and greater species diversity, and Category 3 sites, which generally display a more impoverished infaunal assemblage.

Substantial differences in species composition were observed among the categories, again between Category 1 and 2 sites compared to Category 3 sites. Generally, clams and gastropods dominated the infauna at Category 1 and 2 sites, whereas crustaceans and polychaetes dominated the infauna at Category 3 sites (Figure 4-3). Moreover, at the species level, the dominant taxa were fairly similar at Category 1 and 2 sites and substantially different from the dominant taxa observed at Category 3 sites. In fact, several of the dominant species at Category 3 sites were either uncommon or absent at Category 1 and 2 sites. Generally, these patterns in species occurrence and assembly attributes (N, H', S) tend to support the contention that disturbance effects increase by treatment category such that Category 1 < Category 2 < Category 3.

Several significant correlations were observed in 1992 between statistics summarizing assemblage attributes and some of the physical and chemical variables examined. Species diversity (H') and number of taxa (S) were negatively correlated with percentage gravel (Pearson Product Moment; $r = -0.60$, $p = 0.05$ and $r = -0.59$, $p < 0.1$, respectively; $df = 9$) but were not correlated with TOC or organic nitrogen. Species diversity and number of taxa were both positively correlated with salinity. In dramatic contrast to 1991 when all assemblage attributes correlated negatively with PAH, however, all assemblage attributes exhibited poor correlations with total PAH in 1992 ($r < \pm 0.29$ in all cases).

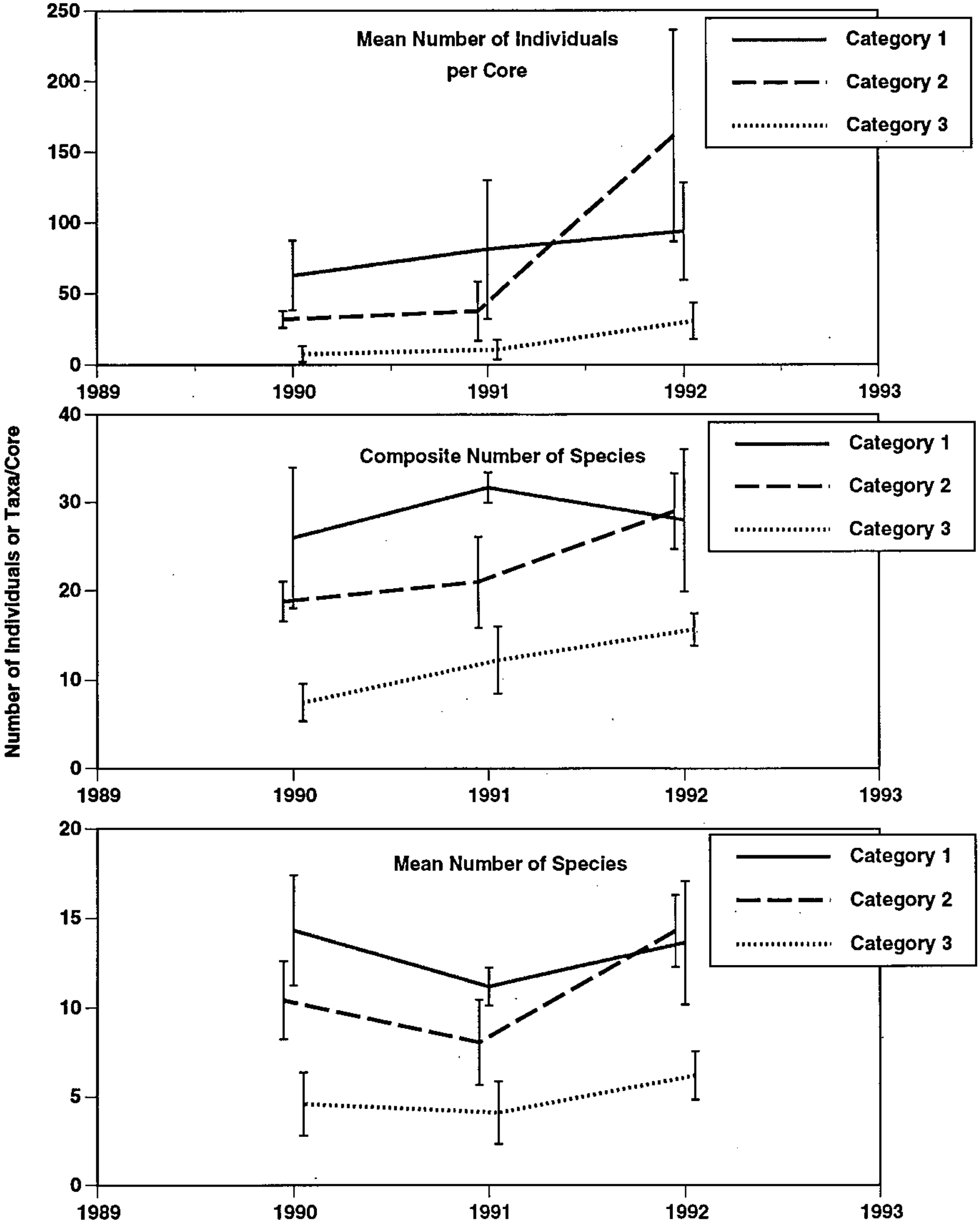

Figure 4-4. Summary indices for infauna from lower intertidal stations, 1990-92.

Table 4-4 Two-way coincidence table showing relationships between species and site groups. Numbers in body of table are average abundance of taxon in cores at site.

		Site Group										
		A1						A2	B1		B2	
Species Group	Taxa	Bainbridge Bight	Outside Bay	Sheep Bay	Block Island	Crab Bay	Herring Bay	Sleepy Bay	Mussel Beach	Snug Harbor	NW Bay West Arm	Shelter Bay
	Mysella tumida	0.00	1.74	1.23	1.23	0.15	1.03	0.15	1.28	0.20	0.15	0.20
	Alvania compacta	0.00	1.00	0.94	0.70	0.20	1.27	0.78	0.73	0.30	0.60	0.15
	Protothaca staminea	0.00	0.83	1.11	1.15	0.20	0.00	0.15	1.02	0.08	0.08	0.08
IA	Eteone longa	0.00	0.82	0.08	1.03	0.38	0.72	0.20	0.92	0.66	0.00	0.15
	Ampithoe kussakina	0.00	0.48	0.70	0.00	0.08	0.95	0.15	0.15	1.23	0.00	0.08
	Pholoe minuta	0.89	0.58	0.41	0.00	0.00	0.38	0.00	0.82	1.31	1.08	0.15
	Fartulum	0.00	1.33	0.95	0.00	0.00	0.86	0.26	0.85	1.32	0.34	0.00
	Cumella vulgaris	0.66	0.15	0.73	0.78	1.13	1.56	0.00	0.08	1.37	0.26	0.38
IB	Macoma balthica	0.45	0.15	0.26	0.53	0.90	0.98	0.00	0.00	0.00	0.00	0.00
	Cingula sp. 1	0.15	1.61	0.00	0.00	1.40	1.82	0.00	0.00	0.08	0.00	0.08
	Nereis vexillosa	0.53	0.08	0.00	0.20	0.00	0.15	0.08	0.30	0.00	0.08	0.38
	Eteone spetsbergensis	0.00	0.00	0.00	0.00	0.20	0.38	0.30	0.00	0.00	0.20	0.08
IIA1	Paramoera sp. 2	0.72	0.00	0.00	0.00	0.00	0.00	0.94	0.00	0.00	0.08	1.11
	Saccocirrus eroticus	0.00	0.00	0.00	0.00	0.00	0.00	1.19	0.00	0.00	0.26	0.00
	Spinulogammarus subcarina	0.00	0.00	0.00	0.00	0.00	0.00	1.16	0.00	0.00	0.00	0.00
	Ianiropsis	0.58	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Lagunogammarus setosus	0.34	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Orbiniella nuda	0.53	0.00	0.08	0.00	0.00	0.00	0.00	0.08	0.00	0.00	0.00
	Owenia fusiformis	0.00	0.00	0.48	0.00	0.00	0.00	0.00	0.08	0.00	0.00	0.00
	Fabriciola berkeleyi	0.00	0.00	0.00	0.00	0.15	0.08	0.00	0.08	1.19	0.00	0.00
IIA2	Leptochelia savignyi	0.00	0.08	0.00	0.00	0.00	0.00	0.00	0.68	0.76	0.15	0.00
	Cirratulus spectabilis	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.15	0.15	0.00	0.00
	Melita californica	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.79	0.00	0.00	0.00
	Golfingia procera	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.38	0.00	0.00	0.00
	Saxidomus gigantea	0.00	0.26	0.00	0.41	0.00	0.00	0.00	0.41	0.00	0.00	0.00
	Leptosynapta	0.00	0.51	0.00	0.00	0.00	0.00	0.00	0.38	0.00	0.00	0.00

Table 4-4 (continued)

		Site Group										
			A1					A2	B1		B2	
Species Group	Taxa	Bainbridge Bight	Outside Bay	Sheep Bay	Block Island	Crab Bay	Herring Bay	Sleepy Bay	Mussel Beach	Snug Harbor	NW Bay West Arm	Shelter Bay
	Odostomia	0.00	0.51	0.53	0.08	0.00	0.75	0.00	0.41	0.00	0.45	0.00
	Macoma inquinata	0.00	0.76	0.58	1.11	0.08	0.64	0.00	0.08	0.00	0.00	0.00
	Pectinaria granulata	0.00	0.45	0.89	0.66	0.00	0.08	0.08	0.00	0.00	0.00	0.00
	Lepidonotus squamatus	0.00	0.76	0.51	0.20	0.00	0.15	0.00	0.00	0.00	0.00	0.00
	Harmothoe imbricata	0.00	0.48	0.20	0.08	0.00	0.15	0.00	0.00	0.00	0.00	0.00
	Glycinde picta	0.00	0.41	0.15	0.08	0.00	0.15	0.00	0.00	0.00	0.00	0.00
	Polydora brachycephala	0.00	0.20	0.08	0.45	0.15	0.26	0.00	0.00	0.00	0.00	0.08
	Barantolla americana	0.00	0.08	0.08	0.26	0.30	0.20	0.00	0.08	0.00	0.00	0.00
IIB1	Armandia brevis	0.00	0.26	0.08	0.30	0.00	0.20	0.00	0.72	0.00	0.00	0.00
	Sphaerosyllis pirifera	0.00	0.34	0.00	0.15	0.00	0.15	0.00	0.78	0.00	0.00	0.08
	Spio filicornis	0.00	0.08	0.00	0.66	0.08	0.08	0.00	0.00	0.00	0.00	0.00
	Polydora quadrilobata	0.00	0.08	0.00	0.20	0.15	0.00	0.00	0.00	0.00	0.00	0.00
	Naineris quadricuspida	0.00	0.08	0.00	0.64	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Mediomastus californiensis	0.00	0.15	0.00	0.08	0.00	0.15	0.00	0.00	0.15	0.00	0.00
	Chiridota	0.00	0.15	0.00	0.00	0.00	0.26	0.00	0.00	0.00	0.00	0.00
	Allorchestes angustus	0.00	0.00	0.00	0.26	0.00	0.26	0.00	0.00	0.68	0.00	0.00
	Exogone gemmifera	0.00	0.00	0.00	0.62	0.00	0.20	0.00	0.20	0.00	0.00	0.00
	Prionospio cirrifera	0.00	0.30	0.26	0.00	0.08	0.00	0.00	0.41	0.00	0.00	0.00
	Ophelia limacina	0.00	0.41	0.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Protodorvillea gracilis	0.00	0.08	0.15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
IIB2	Capitella capitata	0.00	0.20	0.15	0.15	0.08	0.00	0.00	0.00	0.00	0.15	0.00
	Prionospio steenstrupi	0.00	0.08	0.08	0.15	0.00	0.00	0.00	0.00	0.00	0.15	0.00
	Syllis elongata	0.00	0.20	0.30	0.89	0.00	0.00	0.20	0.00	0.08	0.00	0.00
	Glycera capitata	0.00	0.26	0.08	0.34	0.00	0.00	0.00	0.08	0.08	0.00	0.00
	Cingula sp. 2	0.00	0.00	0.00	0.00	0.00	1.40	0.00	0.00	0.00	0.00	0.00
	Ampithoe dalli	0.00	0.00	0.00	0.00	1.34	0.00	0.00	0.00	0.00	0.00	0.00
	Pontogeneia ivanovi	0.00	0.00	0.00	0.00	0.00	0.00	0.75	0.00	0.00	0.00	0.00
	Cryptomya californica	0.00	0.08	0.00	0.00	0.08	0.00	0.00	0.00	0.00	0.00	0.00
	Tharyx multifilis	0.00	0.66	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Scoloplos armiger	0.00	0.56	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 4-5. Mean abundance and intensity of occurrence (fidelity) for taxa in species groups within site groups based on two-way coincidence table.

		Site Group			
Species Group	Variable	A*	B1	B2	Overall
IA	Mean	0.56	0.78	0.23	0.51
	SD	0.49	0.43	0.27	0.47
	Fidelity (%)**	0.71	1.00	0.79	0.79
IB	Mean	0.74	0.25	0.08	0.47
	SD	0.28	0.50	0.13	0.56
	Fidelity (%)	0.89	0.50	0.50	0.67
IIA1	Mean	0.08	0.03	0.39	0.15
	SD	0.17	0.09	0.45	0.31
	Fidelity (%)	0.08	0.10	0.70	0.36
IIA2	Mean	0.05	0.23	0.00	0.07
	SD	0.14	0.33	0.03	0.19
	Fidelity (%)	0.17	0.55	0.05	0.20
IIB1	Mean	0.18	0.09	0.01	0.12
	SD	0.24	0.21	0.05	0.21
	Fidelity (%)	0.59	0.24	0.09	0.39
IIB2	Mean	0.10	0.05	0.02	0.07
	SD	0.17	0.11	0.06	0.14
	Fidelity (%)	0.48	0.29	0.14	0.35

* Sleepy Bay was not included in view of poor association with the group.

These relationships appear at odds with the strong differences observed between Categories 1 and 2 and Category 3, and it is interesting to ask what factors related to the oil spill and the associated shoreline treatment program are still acting to inhibit recovery at the Category 3 sites. This apparent lack of a detectable community response to a wide range of hydrocarbon concentrations (from below detection to 780 ppb) implies that hydrocarbon concentrations in the sediments are no longer influencing the condition of the infaunal community appreciably. Recovery of the infaunal assemblages, however, may lag several years behind chemical restoration of the habitat. In addition, the data indicate that PAHs may still have been affecting *Protothaca* growth rates in 1991 (Chapter 5), and so residual PAHs may be causing other chronic effects not detectable in the assembly attributes.

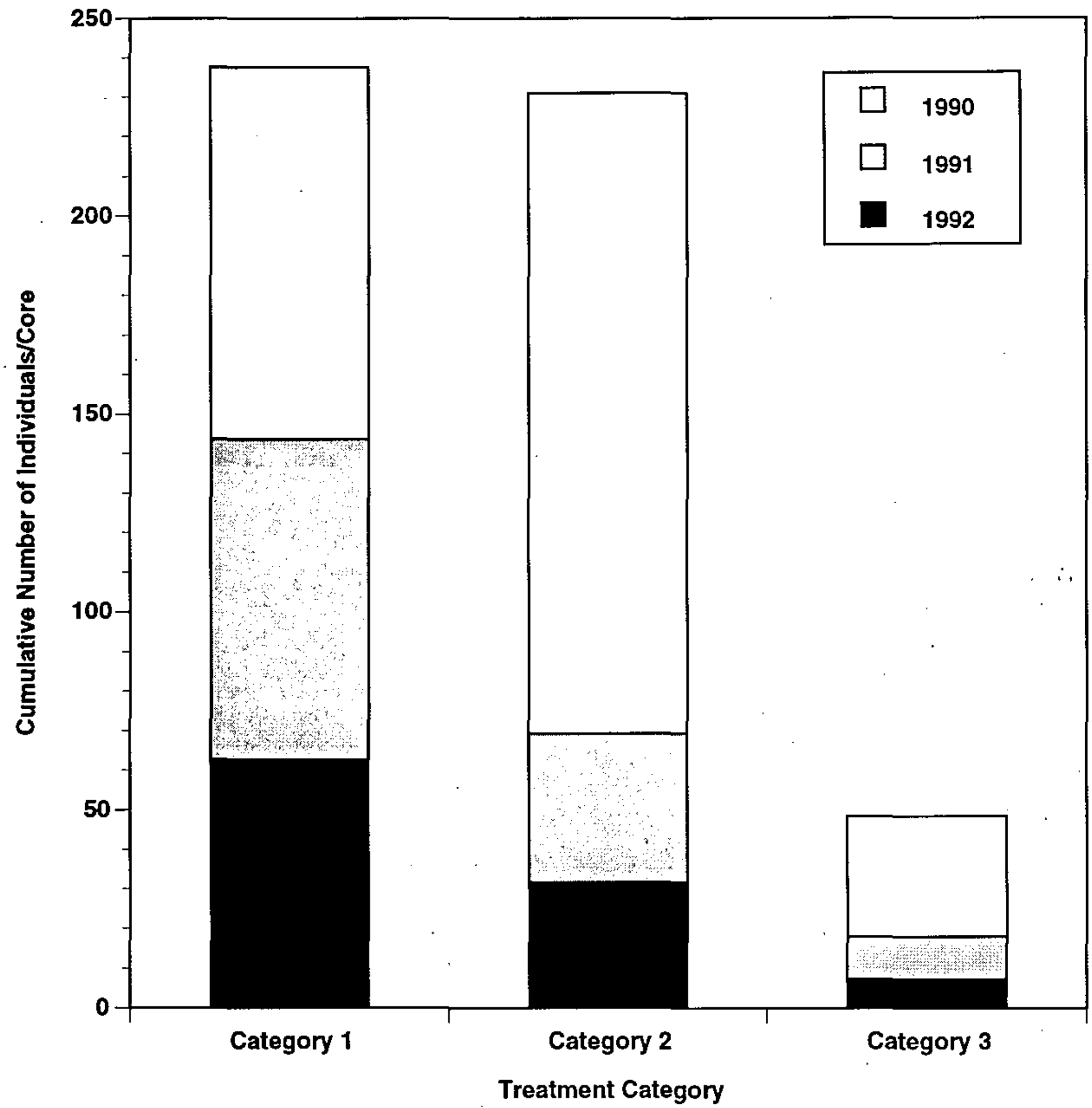

Figure 4-5. Cumulative number of individuals per core for each category from lower intertidal stations, 1990-92.

Factors that could cause the differences among the treatment categories to persist include altered sediment conditions or biological phenomena such as succession. Such factors require the passage of time before they are resolved. For instance, stochastic physical and biological processes (random chance) associated with larval availability for recruitment to disturbed areas and survival of recruits may play a major role in the succession associated with recovery. In a detailed description of the unpredictability of larval availability and recruitment for infaunal polychaetes and bivalves, Feller et al. (1992) reported that coupling between larval availability and recruitment was poor and that variability in settlement was high between years. Before finally selecting a suitable site, juveniles of some species actively move by drifting periodically in the current for more than a year after initial settlement (Armonies and Hellwig-Armonies, 1992). Where an adult population of this type is eradicated, the recovery process could require several years for the adults to regain their former density. The interactions of weather and tides are another random influence on survival of larvae and recruits.

Exclusive of the effects of hydrocarbons, several biological phenomena associated with damage and succession and could influence recovery. Kukert and Smith (1992) found that burrowing is an important means of dispersal during recolonization. Moreover, Thrush et al. (1992) found that addition of adult polychaetes and bivalves (through immigration, for example) to defaunated sediments facilitated recolonization by a variety of colonizers and caused increased species diversity and density where they occurred. In a case where damage to the biota is extensive and widespread (e.g., Category 3 sites following shoreline treatment), the reduced state of existing populations may inhibit recolonization in several ways: by reductions in generation of gametes and juvenile recruits; by reduced "facilitation" of settlement from the plankton; and by reduced immigration of adults.

In a study of macrofaunal recolonization in defaunated eutrophic sediments heavily dosed with crude oil (upper layer of sediment with 4,200 ppm North Sea crude oil), Berge (1990) found that the infauna showed substantial recovery within three to four months, but asymptotic species richness was nearly 40 percent lower than the reference tests and required 14 months for full recovery. Similar reductions were observed in infaunal abundance and biomass in the oiled sediments. Berge reported substantial depression in bivalve abundance and elevated abundance of polychaetes and crustaceans in the oiled sediments, as has been seen in Prince William Sound.

A reason that Berge (1990) observed more rapid recovery than the authors have observed in Prince William Sound may be related to methods. Berge defaunated sediments by freezing so that most sediment quality characteristics were fixed. In contrast, sediment characteristics in Prince William Sound were greatly modified by the treatment process.

Spies et al. (1988) compared the effects of equal doses of crude oil and kelp on macrofaunal infauna and meiofauna and determined that both materials caused elevated abundance at low concentrations (0.1 percent) and depression at higher concentrations (5 percent). Spies et al. concluded that toxicity from by-products (e.g., H_2S) of microbial metabolism of the added organic materials was the main cause of reduced density of the infauna. These observations probably help explain both the sharp elevation in abundance observed in 1992 at Category 2 sites (Figure 4-4), where organic carbon and nitrogen are substantially higher than reference sites (Appendix Table A-6), and the prolonged paucity of infauna at Category 3 sites, where organic materials remain substantially depleted following shoreline treatment. Thus, the initial depressions in numbers of specimens and taxa observed in 1990 for Category 2 sites were probably due to a combination of acute toxicity arising from lighter fractions in the crude oil followed by H_2S and low dissolved oxygen or anaerobic conditions in the sediments as a result of organic enrichment. In fact, we noted anaerobic conditions in sediments at numerous heavily oiled sites by July 1989 (D. C. Lees, Ogden Environmental and Energy Services Company, personal observation).

The prospect that silt composition in the sediments will recover appreciably at most treated sites in the near term is low (M. O. Hayes, Research Planning, Inc., personal communication). A large proportion of the treated sites in Prince William Sound is located on islands, a considerable distance from glaciers or other major sources of suspended inorganic particulates. As a consequence, concentrations of suspended solids in the water are generally quite low, and sediment deposition rates are very slow.

Long-term Trends

Abundance data for several major infaunal taxa suggest long-term trends that may be associated more with recovery than with climatic phenomena. This premise is based on a comparison of temporal patterns in abundance of major taxa at Category 1 lower stations with patterns at Category 2 and 3 lower stations (Figure 4-5). Four temporal patterns in abundance are possible for this sampling scheme. These include a steady increase, a steady decline, an increase followed by a decrease (temporary peak), and a decrease followed by an increase (temporary decline). No taxon in any treatment category exhibited a steady decline. In the absence of a long-term trend associated with climatic change or recovery, one would expect changes in abundance to be fairly nondirected or random.

Based on the major macroinfaunal taxa, this expectation was satisfied at Category 1 sites, where three types of change were evenly represented (Figure 4-3): two taxa exhibited steady increases; one showed a temporary peak; and one showed a temporary decline. Gastropods increased somewhat between 1990 and 1991, and crustaceans became appreciably more abundant in 1992 than in 1990, but the remaining taxa exhibited no real change. In contrast, steady increases were the more common changes in Categories 2 and 3. In the former, three major taxa increased steadily, and one taxon exhibited a temporary decline. All taxa were considerably more abundant in 1992 than in 1990 including polychaetes, which declined temporarily in 1991. In Category 3, three taxa increased steadily, and one peaked temporarily (Figure 4-3). Three taxa were somewhat more abundant in 1992 than in 1990, whereas bivalves declined slightly over that period. While not definitive, these contrasts in temporal patterns suggest that changes in abundance are nonrandom at Category 2 and 3 sites.

The relative abundance of the major macroinfaunal taxa differed consistently among the treatment categories. The dominant groups at Category 1 lower stations were polychaetes, bivalves, and gastropods (Figure 4-3). Abundance of these taxa was fairly stable from 1990 through 1992. Crustaceans, in contrast, became dramatically more abundant in all treatment categories in 1992.

Patterns in abundance of the major macroinfaunal taxa in Category 2 differed from those described above for Category 1. First, the abundances of the major taxa in Category 2 were substantially lower in 1990 and 1991 than they were in Category 1 (Figure 4-3). Second, nearly all taxa experienced an extraordinary increase in abundance in 1992.

In Category 3 the dominant macroinfaunal taxa were polychaetes and crustaceans (Figure 4-3). Bivalves and gastropods were of secondary importance. All groups were poorly represented, and density was much lower than in the other treatment categories.

Comparing general abundance with the other treatment categories shows that, while Category 3 exhibited signs of recovery, infauna at these sites has suffered serious degradation. It appears that several more years will be required before the infauna at Category 3 sites resembles that at Category 1 and 2 sites.

Infaunal assemblage attributes also provide insight into long-term trends. Average number of individuals/core (N) appears to have been increasing steadily in all three treatment categories since 1990 (Figure 4-6), although the increase was not statistically significant in Category 1. In 1990 and 1991 N was highest in Category 1 and was significantly higher in Categories 1 and 2 than in Category 3. In 1992, N in Category 2 increased significantly (randomization ANOVA; $p = 0.005$) and exceeded that in Category 1; the increase in N over time was also significant ($p = 0.09$) at Category 3 sites; N is still significantly higher in Categories 1 and 2 than in Category 3. The nearly fourfold increase in N in Category 2 suggests that the biota was responding to factors not experienced at Category 1 and 3 sites. The findings of Spies et al. (1988) lend credence to the hypotheses that the differences may be due to organic enrichment at Category 2 sites. The increase in S from 1990 through 1992 was significant at Category 2 sites ($p = 0.08$) but not at any other category.

It appears that the cumulative number of infaunal individuals/unit area at Category 1 and 2 lower mixed-soft stations has equalized over the study period (Figure 4-7). In contrast, Category 3 had only about one-fifth the cumulative number of individuals/unit area. Differences between years have been minimal in Category 1, whereas Category 2 and 3 both underwent relatively large increases in 1992. These increases may reflect a response to: benign environmental conditions in 1992 and a combination of recovery and surplus in required resources following the stress associated with the oil spill and the treatment. The quicker response in Category 2 may be due to a lesser degree of initial stress and greater availability of organic nutrients, although the increases at Category 2 and 3 sites may be a direct or indirect response to the spill and the ensuing shoreline treatment.

Number of species/core (Figure 4-4) reflects conditions in species richness at the small scale. As was described for abundance, species richness (S) was highest at Category 1 sites in 1990 and 1991 and was significantly higher in Categories 1 and 2 than in Category 3. Number of species declined in all categories in 1991 and increased in 1992, but none appeared to change appreciably at the small scale over this period. Reflecting conditions on a larger, site-wide scale, composite number of species exhibited a pattern similar to that described for abundance. The initial relationships among the categories were the same: all categories tended to increase over the period of the study, but both Categories 2 and 3 appeared to increase substantially while Category 1 was basically static.

Species diversity (H') was quite stable over the study period (Figure 4-4). These temporal patterns do not provide compelling evidence of recovery or long-term trends, although the patterns reinforce the conclusions stated above regarding the relationships among the treatment categories. On both the small scale and a site-wide basis, species diversity in Category 3 was substantially lower than in Categories 1 and 2. We have not observed the wide fluctuations in infaunal indices previously reported by Sanders (1978) in several infauna parameters at heavily oiled stations following the Buzzards Bay spill.

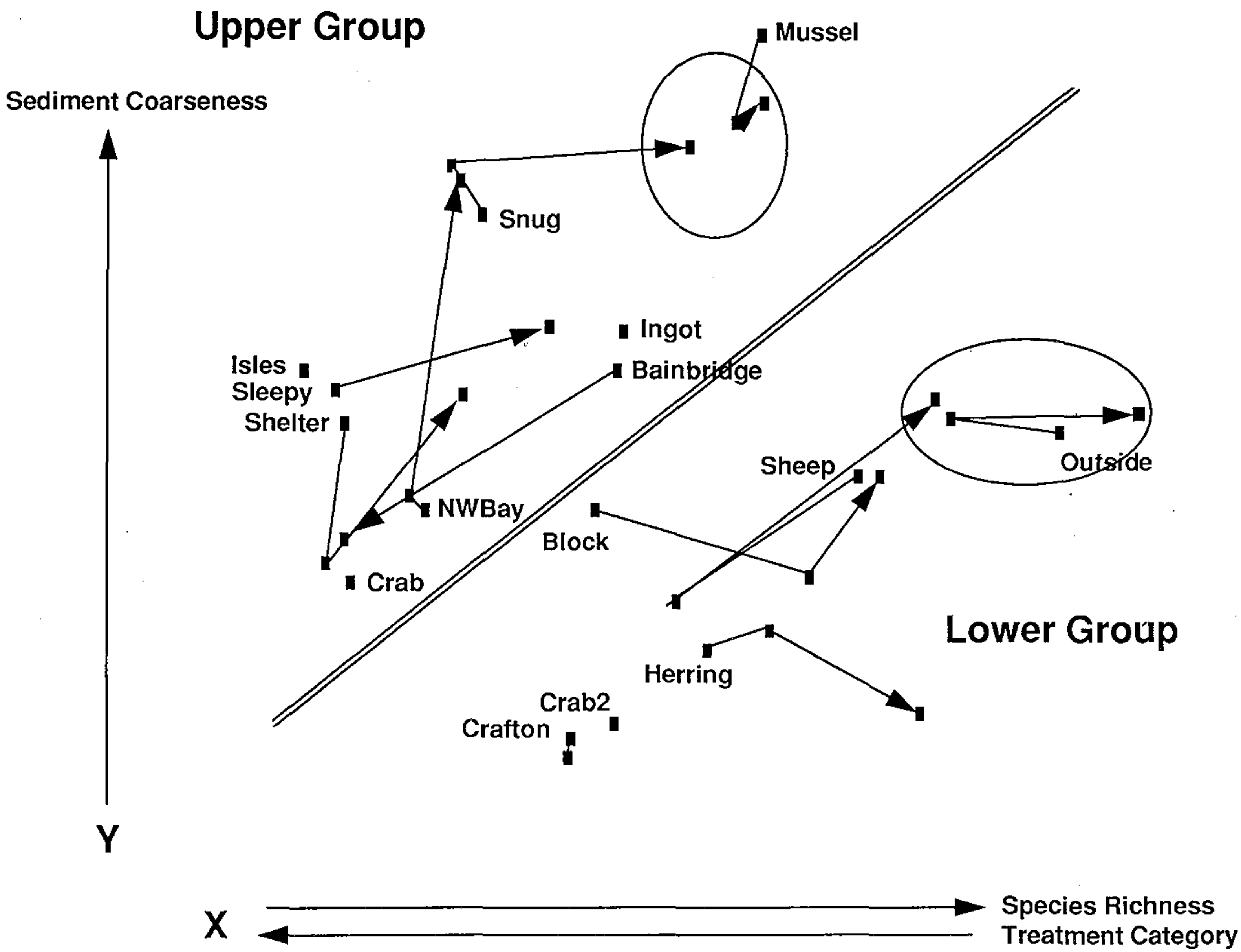

Figure 4-6. Principal component analysis of infauna abundance at all stations, 1990-92.

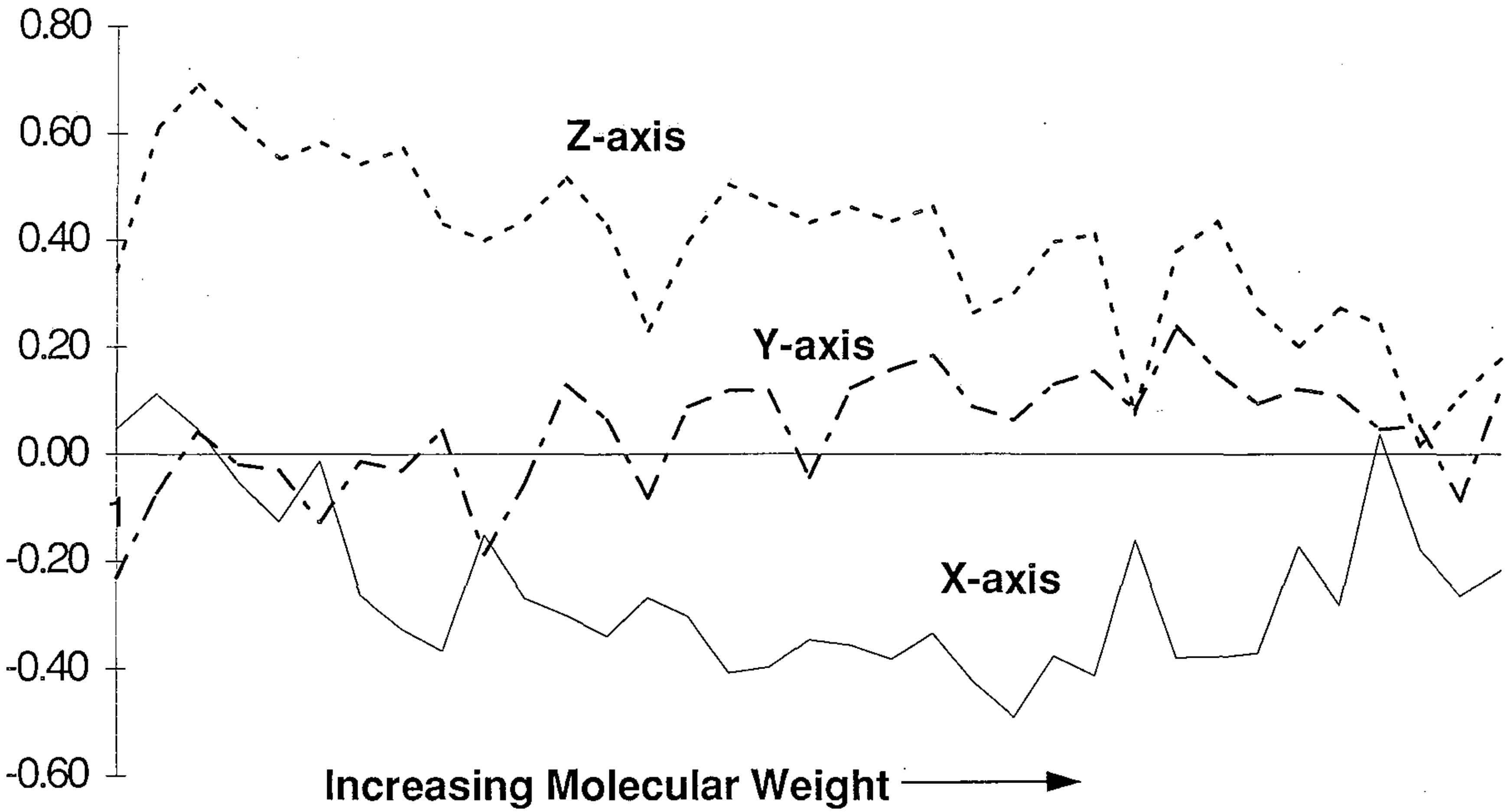

Figure 4-7. Correlations of infauna PCA axes (station scores) with PAH compounds.

Major factors influencing rates of recovery probably include concentrations of organic material, sediment grain size, salinity, fecundity, motility of propagules, and the severity of the initial damage incurred by the biota as the result of the toxicity and organic loading from the oil. Hydraulic treatments caused long-term alterations of two of these factors (grain size, organic content) that now appear to be slowing recovery. If one assumes that Category 1 represents the undisturbed condition and Categories 2 and 3 represent stages in recovery, the relationships described above suggest that the infaunal populations at Category 2 sites have nearly recovered and that populations at Category 3 sites have been severely disturbed but are recovering. As has been reported previously (Berge, 1990), crustaceans and polychaetes appear to be recovering more rapidly than gastropods or bivalves; alternatively, they may represent earlier stages of succession. Among these taxa the bivalves appear to be recovering most slowly.

Recovery of hardshelled clams to prespill conditions is not expected for many years (Chapter 5). Remnant beds of hardshelled clams lying above or on the upper portions of beaches in areas uplifted by the Alaska earthquake of 1964 (Baxter, 1971) provide a benchmark against which the recovery rate of clam populations in the intervening 29 years may be gauged. Comparison of 1964 size structure and species composition with present populations suggests that even more than 25 years may be required to achieve recovery (D. C. Lees, 1992, Ogden Environmental and Energy Services Company, personal observation).

A return to prespill conditions of smaller infauna is expected to occur more rapidly than for larger, long-lived infauna. For example, Wormald (1976) found a "normal" meiofaunal assemblage of nematodes and harpacticoids within 18 months following a diesel spill on a sandy beach. More recently, Feller et al. (1992) reported that the meiofauna recovered much more rapidly from disturbance in soft-bottom habitats that did larger polychaetes and bivalves.

Multivariate Analysis of 1990-92 Infauna Data

To track the yearly trends and relationships in the infaunal assemblages, an analysis of species abundance at all stations was conducted using PCA. From the resulting scores, graphical relations, and subsequent comparisons, the following trends were noted:

- ❐ The infaunal data set represents two groups of stations:

  In the PCA graph two groups of stations are apparent in roughly parallel bands that lie diagonally across the axes (Figure 4-8). Based on correlation analyses between the PCA scores and various parameters (discussed below), the upper group comprises stations that are less species rich and have coarser grain size. This group includes the Category 3 stations, the more impoverished of the Category 1 stations, and various Category 2 stations. With exception of two somewhat anomalous stations, this group corresponds to Site Group B from the 1992 cluster analysis (Figure 4-3). The lower group (approximately corresponding to Site Group A in Figure 4-3) has higher species richness and higher proportions of fine grain sediments; it includes a mix of Category 1 and 2 stations.

- ❐ Converging annual trends suggest recovery is occurring within two station groups:

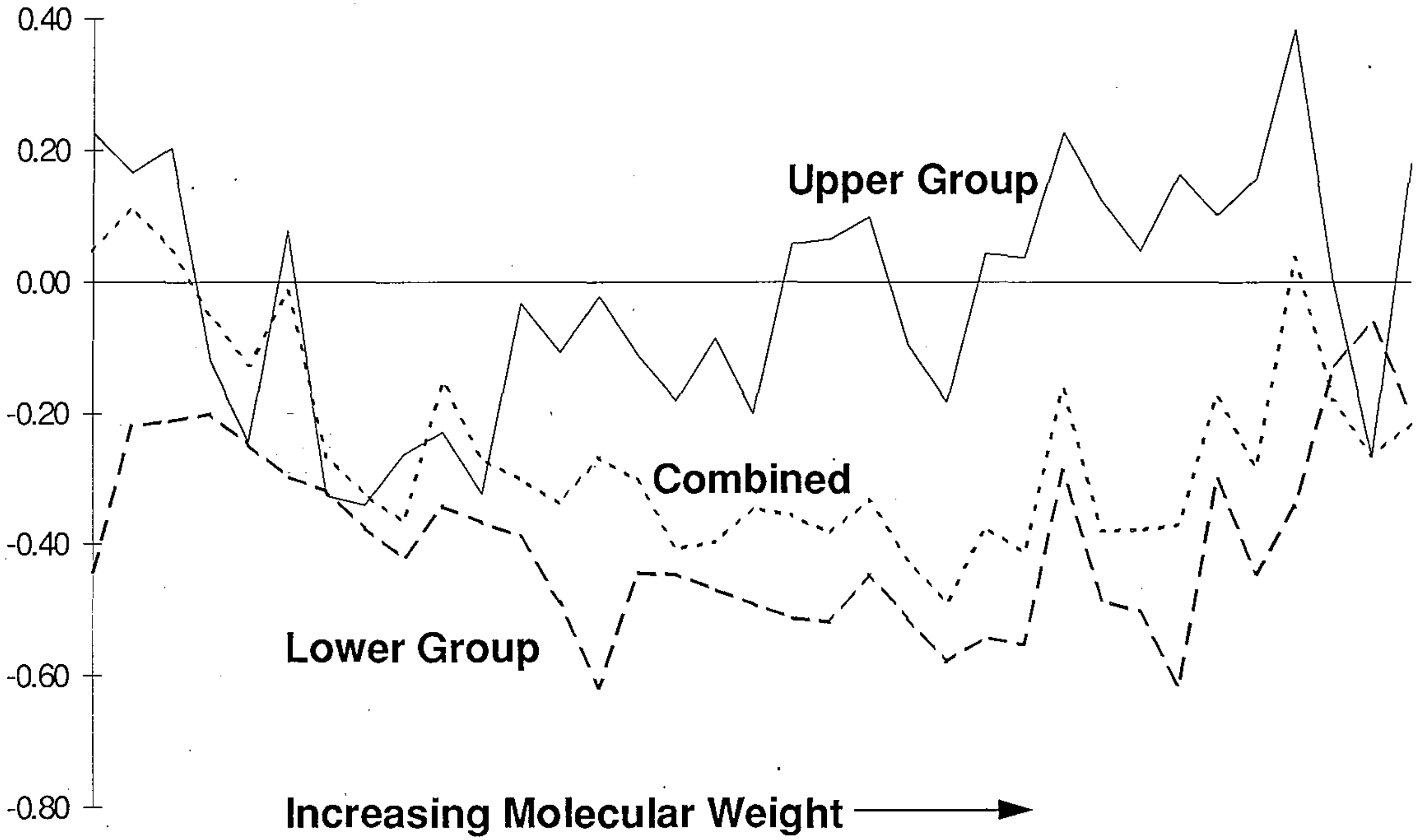

Figure 4-8. Comparison of PAH compounds correlation with infauna PCA stations groupings (x-axis station scores).

> Based on the progression of annual changes within these groups (shown in Figure 4-8 by the connecting lines between years), the trend suggests that recovery within each group occurs along a "track" with a dynamic endpoint toward the upper right (circled in the figure). The upper group endpoint appears to be an assemblage similar to the Snug Harbor or Mussel Beach stations. The lower group movement is toward the Outside Bay, Block Island, and Sheep Bay assemblages.

The X-axis correlates with a gradient of species richness and treatment categories, and the Y-axis correlates with grain size distribution (Table 4-6). The Z-axis (of minor concern) correlates with oiling parameters.

The X-axis correlates -0.54 with treatment categories, 0.68 with total abundance, and 0.93 with species richness and thus confirms the general trend of impacted Category 3 stations to the left and Category 1 stations to the right. The central three stations (Bainbridge Bight, Ingot Island, and Sleepy Bay) are very poorly represented by the PCA axes (the stations' assemblages were either mixed or unique relative to the species abundance trends at the other stations) but still are placed in the graph based on their final (albeit nonrepresentative) scores.

The Y-axis correlates 0.67 with the coarsest individual grain sediment fraction, 0.82 with the coarse grain group (> 1 mm), -0.71 with the mid-sized grains (250 microns to 1 mm), and -0.57 with the finest grains (< 250 microns). The stations highest on the Y-axis comprise species that are tolerant of or prefer the coarser grain sediments.

The Z-axis is of minor concern to the PCA analysis (holds little significance regarding the structure of the results) but correlates moderately (maximum 0.62) with a variety of PAH compounds, especially the low molecular weight compounds such as naphthalenes and fluorenes. The X-axis showed mild negative correlations (maximum -0.49) with PAH compounds and peaked within the mid-molecular weight compounds (Figure 4-7). Total PAH correlated -0.35 with the X-axis compared to 0.36 with the Z-axis; this pattern suggests that total residual oil is a factor but probably not dominant in determining species distributions.

In Figure 4-6 even the most stable stations (e.g., Mussel Beach, Outside Bay) still show movement representing annual variation and regional community shifts. Some stations show radical shifts, both positive and negative.

The Category 3 lower mixed-soft station at Northwest Bay West Arm made a dramatic leap ahead of the other Category 3 stations along the recovery track during the past year, mostly due to the appearance of several opportunistic polychaete species. Conversely, the Bainbridge Bight control was severely affected by an unknown cause; the resulting species impoverishment pushed its scores to the bottom of the group. Because this site is located in the western sound, exposed to an ocean entrance, and near a glacier, physical environmental impacts are a potential cause. In the lower group a shift in the assemblage at the Herring Bay station has moved it in a new direction. The Sheep Bay station has apparently recovered from the impact of unknown origin noted in 1992.

Table 4-6 Correlations of PCA scores with sediment grain size fractions and summary indices. (PCA groups coded 1 for lower group, 2 for upper group).

	12.5 mm	6.3 mm	2 mm	1 mm	500 µ	250 µ	125 µ	63 µ	Silts	Gravel	Sands	Fines	Treatment Category	N	S-pooled	S-avg	H'-pooled	H'-avg	PCA Scores X	PCA Scores Y	PCA Scores Z	PCA Grp
12.5mm	1.00																					
6.3mm	-0.36	1.00																				
2mm	-0.55	0.68	1.00																			
1mm	-0.61	-0.04	0.35	1.00																		
500 µ	-0.58	-0.24	0.13	0.77	1.00																	
250 µ	-0.47	-0.39	-0.09	0.43	0.71	1.00																
125 µ	-0.58	-0.11	-0.19	0.29	0.31	0.42	1.00															
63 µ	-0.51	0.00	-0.09	0.15	0.09	0.12	0.85	1.00														
Silts	-0.48	-0.18	-0.20	-0.05	0.10	0.26	0.61	0.59	1.00													
Gravels	0.77	0.27	0.04	-0.57	-0.70	-0.73	-0.78	-0.61	-0.70	1.00												
Sands	-0.64	-0.26	0.14	0.84	0.95	0.83	0.39	0.14	0.12	-0.77	1.00											
Fines	-0.57	-0.16	-0.20	0.06	0.16	0.31	0.82	0.79	0.95	-0.79	0.21	1.00										
Trt. Cat.	0.19	0.04	0.23	0.19	0.03	-0.06	-0.50	-0.56	-0.46	0.32	0.06	-0.54	1.00									
N	-0.30	0.02	0.23	0.14	0.04	0.07	0.07	0.22	0.33	-0.25	0.09	0.29	-0.38	1.00								
S-pooled	-0.16	0.08	0.02	-0.06	-0.18	-0.02	0.12	0.23	0.35	-0.14	-0.10	0.31	-0.55	0.62	1.00							
S-avg	-0.20	0.12	0.07	-0.03	-0.16	-0.01	0.12	0.26	0.34	-0.16	-0.07	0.31	-0.61	0.76	0.95	1.00						
H'-pooled	0.12	0.06	-0.10	-0.30	-0.41	-0.15	0.07	0.18	0.12	0.12	-0.33	0.13	-0.45	0.30	0.78	0.74	1.00					
H'-avg	0.08	0.10	-0.14	-0.36	-0.45	-0.11	0.10	0.22	0.23	0.07	-0.34	0.22	-0.61	0.37	0.84	0.84	0.88	1.00				
X	-0.15	0.07	-0.03	-0.02	-0.12	-0.01	0.08	0.20	0.35	-0.16	-0.05	0.29	-0.50	0.70	0.94	0.94	0.66	0.75	1.00			
Y	0.67	0.17	-0.03	-0.42	-0.70	-0.71	-0.60	-0.33	-0.53	0.82	-0.71	-0.57	0.17	-0.26	0.01	-0.04	0.20	0.19	-0.06	1.00		
Z	0.14	0.12	-0.16	-0.02	-0.02	0.03	0.01	-0.19	-0.27	0.14	0.00	-0.22	0.06	-0.38	0.14	0.05	0.40	0.26	0.05	0.09	1.00	
PCA Group	0.49	0.09	0.11	-0.21	-0.38	-0.44	-0.45	-0.29	-0.61	0.63	-0.40	-0.58	0.45	-0.51	-0.60	-0.62	-0.33	-0.40	-0.70	0.66	-0.10	1.00

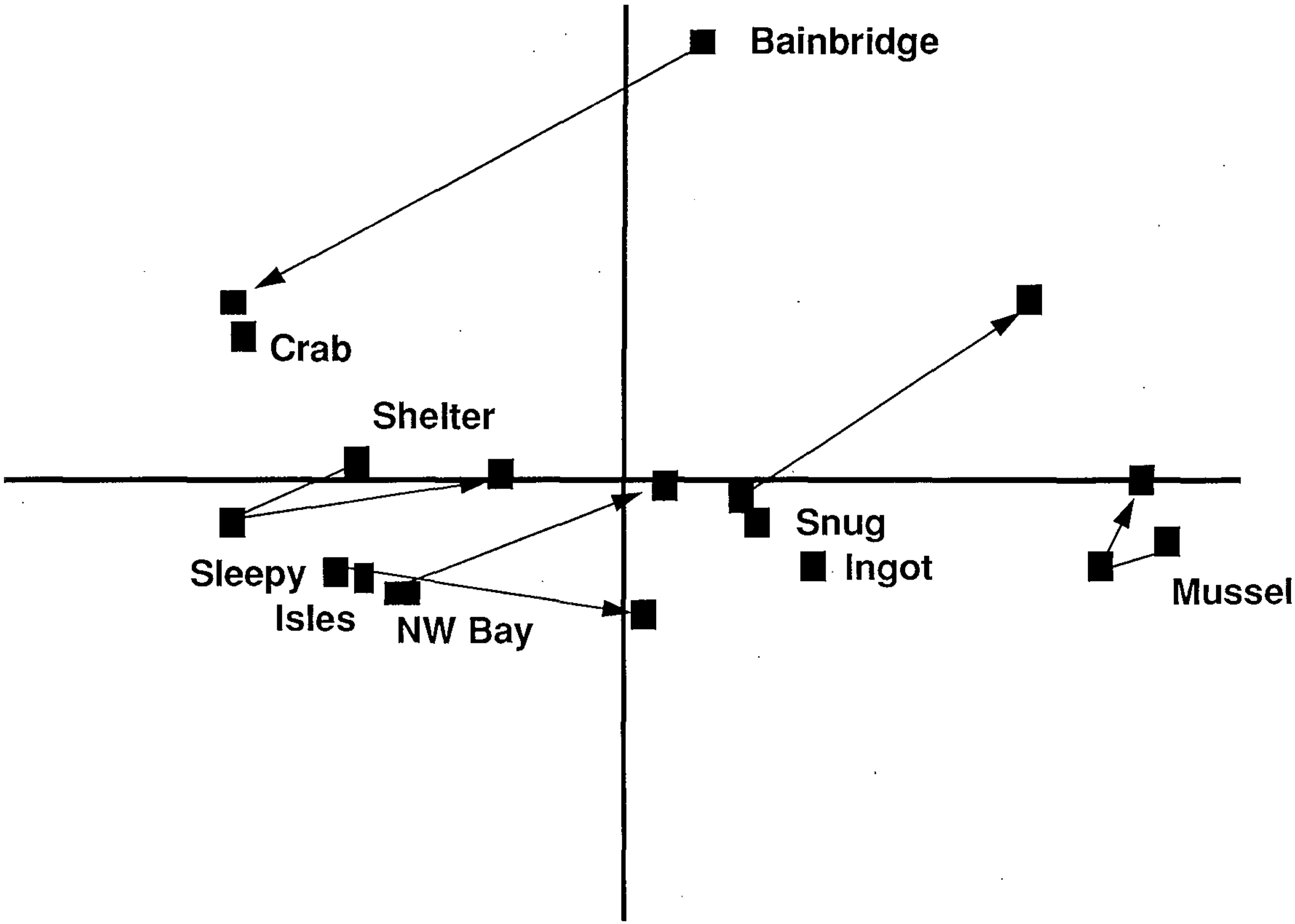

Figure 4-9. Principal component analyses of infaunal species abundance for Upper station groupings.

Upper/Lower Group Comparisons

To elucidate the differences between the upper and lower station groups, a series of exploratory and inferential procedures was used. First, to confirm that the groupings are not just a fluke of multivariate mathematics, various t-tests (Appendix Table D-5) verified that there are significant differences between the groups in species richness, total abundance, and in pooled sediment grain size fractions (gravel, sand, and fines). In correlation tests (Figure 4-8, the lower group is more strongly negatively correlated with PAH compounds than the upper group. This may imply that the upper group comprises a more oil-tolerant assemblage.

Second Phase Principal Component Analysis

A second round of PCA exploration focusing on each grouping was initiated to ascertain trends, commonalities, and differences in species importance between the two groupings. Comparison of the results of two separate PCAs identified species in Table 4-7 that were important (highly weighted scores) in the X-axes of both the upper and lower groups (see Appendix Table D-5 for full lists). There also were significant differences in various taxa between the groups, however. It should be noted that the species in common were mostly mollusks; the differences involved mostly polychaetes (Table 4-8).

The Y-axes were even more dissimilar between the two groups than were the X-axes (Appendix Table D-6). The upper group Y-axis weighted the cumacean *Cumella vulgaris* (0.81) and the spionid polychaete *Polydora quadrilobata* (0.79) as the top two species and the bivalve *Protothaca staminea* and gastropod *Alvania compacta* (-0.33, -0.31, respectively) as the bottom (negative) two species. In contrast, the Y-axis of the lower group was driven at the top by the polychaetes *Syllis elongata, Capitella capitata*, and *Pectinaria granulata* (0.77, 0.70, 0.67, respectively), and at the bottom the gastropod *Cingula* sp. 1 (-0.87) and the amphipod *Ampithoe kussakina* (-0.83).

Based on the overall structures of the two PCAs (Figures 4-9 and 4-10; Appendix Tables D-7 and D-8), it is notable that the upper group reformed into essentially the same pattern seen in the previous PCA using all stations. Viewed from a procedural perspective with the focus on a single group, the analysis would be expected to spread the stations across the graph because differences within the station group are emphasized and the commonalities that distinguished this group from the lower group are negated. In the upper group PCA, however, a tight band of stations formed along the X-axis (the Category 1 stations Bainbridge Bight and Crab Bay were notable outliers) and thereby reinforced the suggestion that the Snug Harbor/Mussel Beach assemblages may represent some form of a recovery endpoint for this group. If this supposition is true, then the Category 3 sites would be expected to progress toward the right in the coming year.

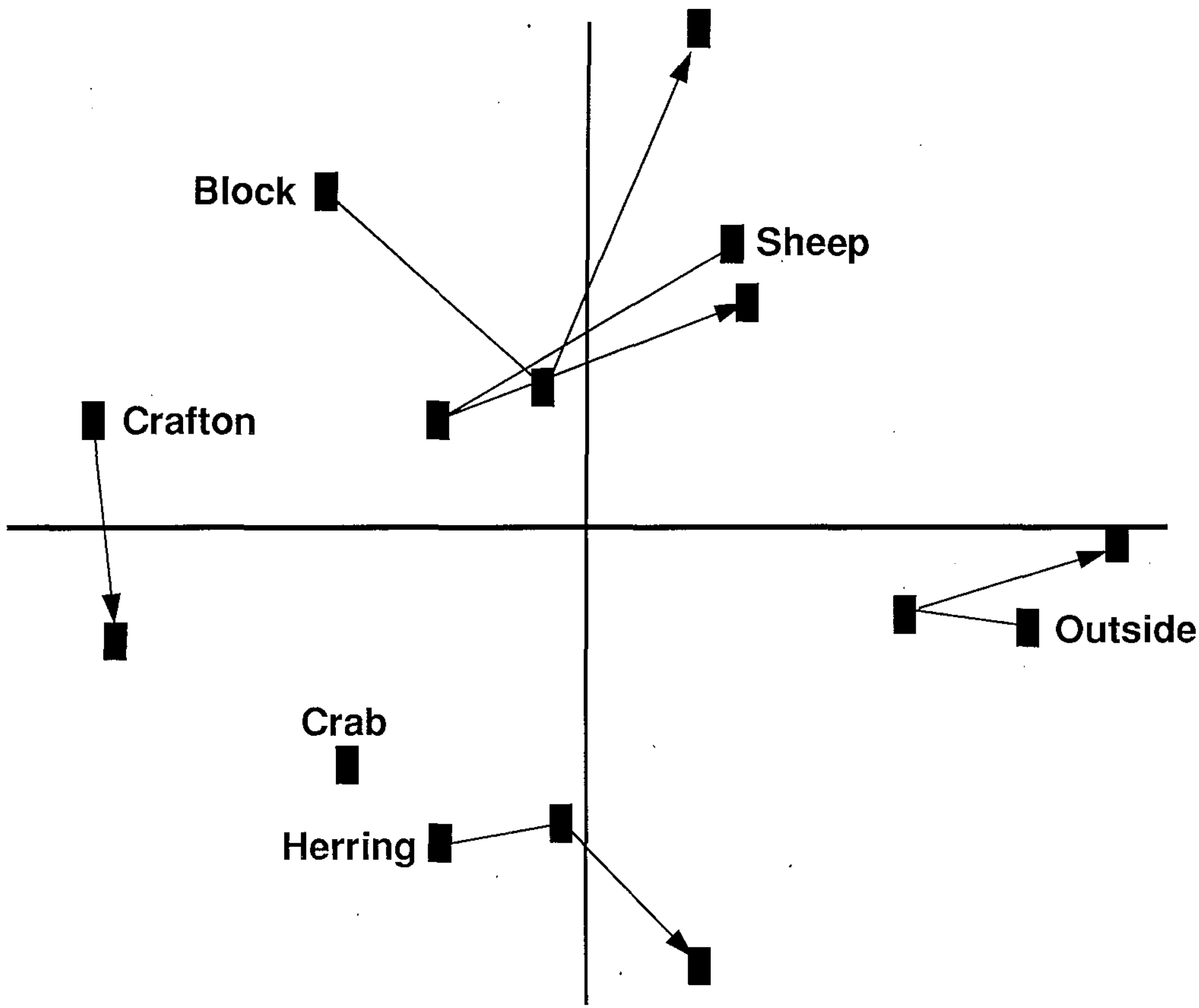

Figure 4-10. Principal component analyses of infaunal species abundance for Lower station groupings.

Table 4-7. Infauna PCA species scores for species important to both station groupings.

Taxon	Upper	Lower
Mysella tumida (bivalve)	0.90	0.93
Fartulum (gastropod)	0.86	0.92
Leptocheila savigniiyi (tananid)	0.82	0.74
Leptosynapta (holothuroid)	0.71	0.65
Saxidomus gigantea (bivalve)	0.78	0.58
Alvania compacta (gastropod)	0.69	0.92
Protothaca staminea (bivalve)	0.61	0.57

Table 4-8. Infauna PCA species scores for species distinctions between the station groupings

Taxon	Upper	Lower
Eteone longa (polychaete)	0.84	—
Ophelia Limacina (polychaete)	—	0.72
Armandia brevis (polychaete)	0.70	—
Modiolus modiolus (bivalve)	0.63	—
Lepidonotus squamatus (polychaete)	—	0.61
Capitella capitata (polychaete)	0.23	0.00
Fabriciola berkleyi (polychaete)	0.44	-0.40
Corophium brevis (amphipod)	-0.07	0.11
Barantolla americana (polychaete)	—	-0.01

Although the stations kept their same general patterns in the PCA of the species-rich lower group, their spread across the axes indicates a greater disparity in species composition. Within this group, there may be no identifiable endpoint but rather several possible endpoints (or dynamic fluctuating endpoints), depending on local conditions. For example, Herring Bay in Figures 4-6 and 4-10 seems to have taken a turn into new territory. This turn is not surprising because a relatively undisturbed, species-rich infauna assemblage still has the normal suite of environmental and species interactions to influence its makeup. In the larger context, however, it still may be possible to discriminate between community types (i.e., the upper and lower groupings) and follow their regional population shifts.

In summary, the PCA generally confirms the site groupings seen in other infaunal analyses and demonstrates that recovery is occurring at all site categories. The PCA also suggests that there may be two different endpoints for recovery, possibly dictated by the physical exposure of the sites.

CHAPTER 5

MOLLUSK STUDIES

INTRODUCTION

Several studies were initiated in 1990 and 1991 to examine some ecological aspects of molluscan species. The littorine snails *Littorina scutulata* and *L. sitkana*, the mussel *Mytilus*, the drill *Nucella lamellosa*, and the littleneck clam *Protothaca staminea* were species of interest.

In an attempt to improve the nature of the data available for comparing growth and mortality rates among treatment categories, a tagging program was initiated to permit direct measurement of growth on individual specimens. Results from tagging studies of these species from 1990 to 1991 may be found in Houghton et al. (1993). Because variability in growth rates was found to be very high in mussels and no evidence of a calcein check could be seen in littorines, these studies were discontinued in 1992.

Target species for continued study were thus *Nucella lamellosa* and the hardshelled clam *Protothaca staminea*. In 1991 *Nucella* were tagged externally with small numbered plastic tags attached to the shell by marine epoxy putty. *Nucella* were recaptured, measured, and released in July 1992 at sites previously studied, but this data set has not been analyzed and is not reported at this time. In May 1991 *Protothaca* were tagged chemically with calcein, a fluorescent dye that binds with calcium in the shell during shell production. Calcein tagging of *Protothaca* revealed a distinct check when examined under an ultraviolet light, and because transplanted clams provided useful information on survival in oil-contaminated sediments, this study was continued in 1992. In addition, *Protothaca* collected in 0.25-m^2 excavations at lower mixed-soft sites in 1992 were measured and aged for growth analysis.

METHODS

Field Transplant Experiment

An experiment to examine survival, growth, and hydrocarbon uptake of clams transplanted to previously oiled sites was initiated during 1992 following a similar experiment done in 1991 (Houghton et al., 1993). Approximately 800 littleneck clams (*Protothaca staminea*) were collected from near the lower reference station at Bainbridge Bight. These animals were immediately placed in a calcein solution for a minimum of 18 hours. At the transplant site at Block Island, wooden quadrats (0.25 m^2) were dug into the sediment flush with the sediment surface. Clams were transplanted into five randomly located quadrats on each of three parallel transects established along the beach contour; two transects were located above the existing lower mixed-soft station, and one was below the station. Sediments within each quadrat were hand-dug to a depth of 10 to 15 cm to loosen the material for planting and to remove indigenous clams for tissue hydrocarbon analysis. A sediment sample was also taken from each of the quadrats for hydrocarbon analysis. Ninety clams of various sizes were buried equally spaced (ten rows of nine) within the quadrats in the middle transect, and 25 clams were buried (five rows of five) in the upper and lower transects. An additional quadrat of 40 clams was placed at the lower station at Mussel Beach South to serve as a reference. All quadrats were left in place and are scheduled to be collected in July 1993.

Age and Growth

At each of the 13 lower mixed-soft stations sampled in July 1992, four randomly located 0.25-m^2 quadrats were excavated and hand-sorted to remove larger bivalves. This method has been found to provide more efficient quantitative sampling of larger hardshelled clams than methods employing screens (Houghton, 1973). Butter and littleneck clams (*Saxidomus giganteus* and *Protothaca staminea*) larger than four to five mm were retained and frozen for length and age analyses in the laboratory.

Because erosion in the umbonal region makes identification of the first annulus difficult on older venerid clams, littleneck and butter clams were aged using a modification of the methods and conventions of Houghton (1973). Specifically, rings less than 2.5 mm long were not counted as annuli, and no first annulus was recorded as greater than 8 mm. When the first distinct ring was greater than 8 mm, this ring was assumed to be the second annulus, and the first annulus was recorded as 2.5 mm. In addition, the external sculpture was filed to aid in distinguishing true annuli from disturbance checks. Total length and lengths of the last three annuli were measured to the nearest tenth of a millimeter for all clams collected from 0.009-m^2 cores and from 0.25-m^2 quadrat excavations. Calcein-marked clams transplanted from Bainbridge Bight in May 1991 and recovered at Bainbridge Bight, Block Island, and Northwest Bay West Arm in September 1991, were also measured and aged.

RESULTS

Distribution and Abundance

The littleneck clam (*Protothaca staminea*) was found in 0.25-m^2 excavations at all lower mixed-soft stations sampled in July 1992. Total numbers in the 1.0 m^2 sampled by the four excavations ranged from a low of two animals at the Category 3 Sleepy Bay station to a high of 420 at the Category 2 Block Island station (Table 5-1). Category 1 and Category 2 sites have had consistently higher abundances of *Protothaca* from 1990 to 1992 (Figure 5-1). The butter clam (*Saxidomus giganteus*) was found in much lower numbers. No *Saxidomus* were found at five stations (Crab Bay, Herring Bay, Elrington Island, Sleepy Bay, and Northwest Bay West Arm). A high of 53 butter clams was found at the Category 2 Mussel Beach South station.

Mean densities of *Protothaca* from the 0.25-m^2 excavations at lower stations were significantly different between categories when tested with a randomization ANOVA ($p = 0.01$; $n = 3, 5$, and 4 for Categories 1, 2, and 3, respectively; Table 5-1). In multiple comparison randomization t-tests no significant difference existed for either species between Category 1 and Category 2 sites. Abundances of *Protothaca* were significantly different between Category 1 and Category 3 sites ($p < 0.01$) and between Category 2 and Category 3 sites ($p < 0.01$). *Protothaca* was most abundant at the Block Island station (105/0.25 m^2), followed by Sheep Bay (58.75/0.25 m^2).

Table 5-1 Hardshelled clam abundance (no./0.25 square m) at lower mixed-soft stations (n = 4 for each station), July 1992. Clams > 5 mm only.

Species/station	Category	Total	Mean	SD	Max	Min	Category mean	Category SD	Randomization ANOVA	Multiple comparison randomization t-tests 1 vs. 2 n = 2,7	1 vs. 3 n = 2,3	2 vs. 3 n = 7,3
Saxidomus giganteus									0.02	0.78	0.0001	0.004
Outside Bay	1	11	2.75	0.96	4	2						
Sheep Bay	1	42	10.50	6.45	19	5						
Crab Bay	1	0	0.00	0.00	0	0	4.42	5.44				
Mussel Beach	2	53	13.25	5.74	18	5						
Herring Bay	2	0	0.00	0.00	0	0						
Snug Harbor	2	1	0.25	0.50	1	0						
Block Island	2	31	7.75	10.44	23	1						
Ingot Island	2	17	4.25	4.03	10	1	5.10	4.26				
Elrington Island W	3	0	0.00	0.00	0	0						
Sleepy Bay	3	0	0.00	0.00	0	0						
Shelter Bay	3	1	0.25	0.50	1	0						
NW Bay W Arm	3	0	0.00	0.00	0	0	0.06	0.13				

Species/station	Category	Total	Mean	SD	Max	Min	Category mean	Category SD	Randomization ANOVA	Multiple comparison randomization t-tests 1 vs. 2 n = 2,7	1 vs. 3 n = 2,3	2 vs. 3 n = 7,3
Protothaca staminea									0.01	0.77	0.0001	0.0005
Outside Bay	1	58	14.50	3.79	17	9						
Sheep Bay	1	235	58.75	13.23	75	47						
Crab Bay	1	62	15.50	6.56	23	10	29.58	25.26				
Mussel Beach	2	176	44.00	20.64	64	22						
Herring Bay	2	15	3.75	3.30	8	0						
Snug Harbor	2	44	11.00	10.55	24	1						
Block Island	2	420	105.00	78.73	222	51						
Ingot Island	2	57	14.25	6.80	21	7	35.60	31.27				
Elrington Island W	3	9	2.25	1.50	3	0						
Sleepy Bay	3	2	0.50	1.00	2	0						
Shelter Bay	3	11	2.75	4.86	10	0						
NW Bay W Arm	3	10	2.50	2.08	5	0	2.00	1.02				

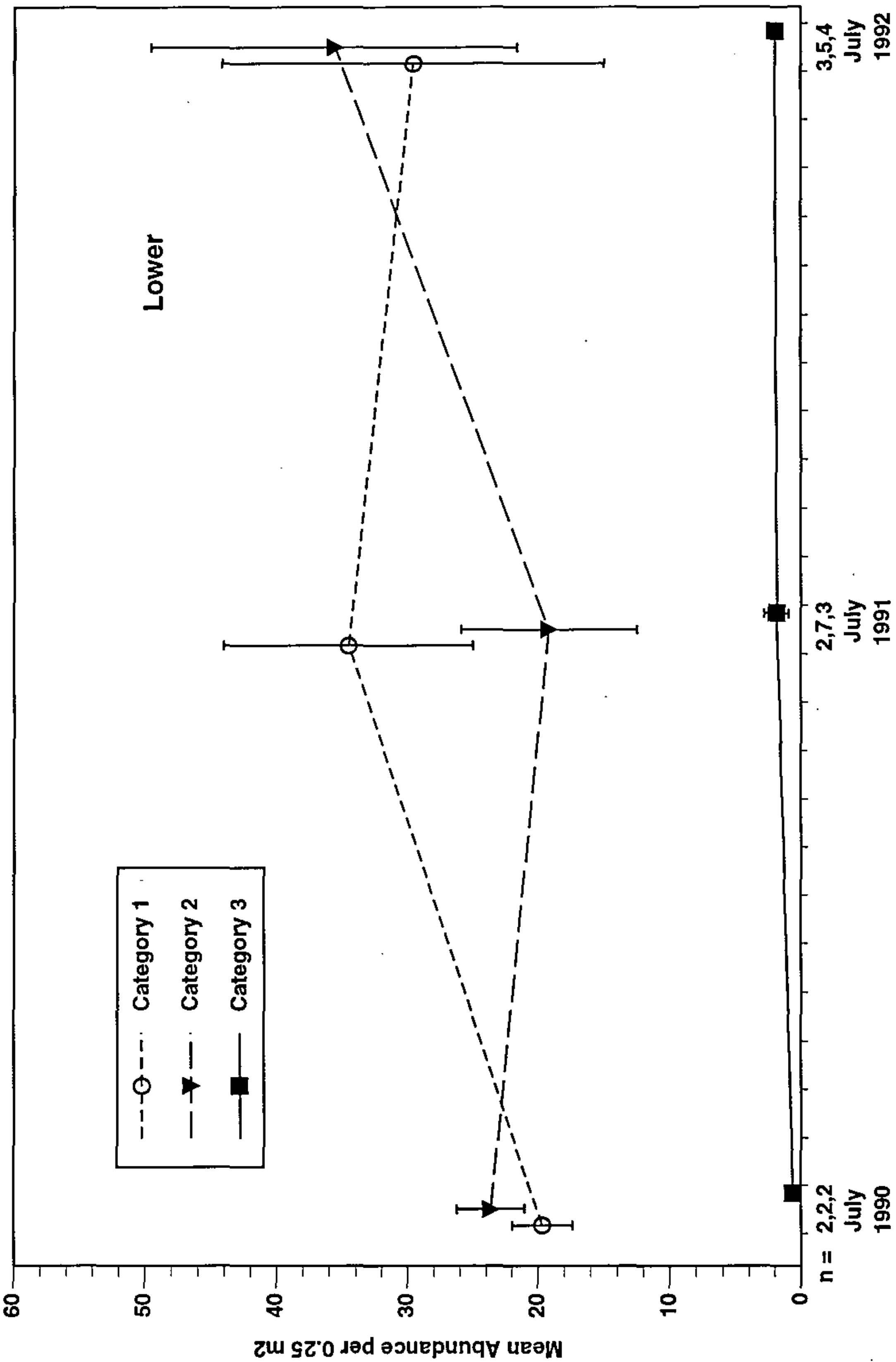

Figure 5-1. Mean abundance of *Protothaca staminea* ±1 SE from 0.25 square m excavations.

Saxidomus was most abundant at the Category 2 Mussel Beach site with 13.25/0.25 m^2; the Sheep Bay Category 1 site was next at 10.5/0.25 m^2 (Table 5-1). There was also a significant category effect among categories for *Saxidomus* in a randomization ANOVA ($p = 0.02$; Table 5-1). Abundances were significantly different between Category 1 and Category 3 and between Category 2 and Category 3 sites ($p < 0.01$ in both cases).

Substantial recruitment of age-zero *Protothaca* from 0.009-m^2 cores was seen at two Category 1 stations (Outside Bay and Sheep Bay) and two Category 2 stations in 1992 (Block Island and Mussel Beach) (Table 5-2). The Category 3 Sleepy Bay station had two age-zero clams. Two sites from each of the three categories did not have any recruitment of *Protothaca*.

Table 5-2. Abundance of age 0 and age 1 *Protothaca staminea* from cores (no./0.009 m^2), July 1992.

Location	Category	Age 0 n	Age 1 n	Total no. clams of all ages	%Age 0 + Age 1 of total
Outside Bay	1	25	2	29	93.1
Sheep Bay	1	46	4	52	96.2
Bainbridge Bight	1	0	0	0	0.0
Crab Bay	1	0	0	0	0.0
Category mean	**1**	**17.8**	**1.5**	**20.3**	
Block Island	2	43	11	62	87.1
Herring Bay	2	0	0	0	0.0
Snug Harbor	2	0	0	1	0.0
Mussel Beach	2	38	3	46	89.1
Category mean	**2**	**20.3**	**3.5**	**27.3**	
NW Bay West Arm	3	0	0	0	0.0
Shelter Bay	3	0	0	1	0.0
Sleepy Bay	3	2	0	2	100.0
Category mean	**3**	**0.7**	**0.0**	**1.0**	

Protothaca Age Structure

Protothaca collected from 0.25-m^2 excavations and 0.009-m^2 cores were aged and lumped by site category (Figure 5-2). Very few clams were found at the Category 3 sites. Most of the Category 3 clams were age zero, age two, and age seven. Category 2 sites had large numbers of age-zero through age-two clams representing animals that settled after the oil spill. Category 2 age structure showed a steady decline in numbers with age that suggests a constant mortality rate over time. Category 1 stations showed a fairly even distribution of age-one through age-six clams with a large recruitment of age zero. This pattern suggests a high initial mortality and a low subsequent mortality rate. This pattern would be expected in a stable, mature population with little opportunity for growth.

Protothaca and Saxidomus Growth

Age and growth of *Protothaca* from each location is summarized in Appendix Tables E-1-1 to E-1-12. Age and growth of *Protothaca* from the transplant experiments is shown in Appendix Tables E-2-1 to E-2-4. *Saxidomus* age and growth are summarized in Appendix Tables E-3-1 to E-3-6.

Protothaca collected from 0.25-m^2 excavations in 1992 were aged, and mean growth of each age class for the years 1989 to 1992 was calculated. Examination of growth rates of (age-class zero to age-class nine) *Protothaca* for the years 1989 through 1992 (Figures 5-3 through 5-6) revealed the following:

- Best mean growth was the 1990 growth of ages three and four *Protothaca* from Category 3 sites (Figure 5-5), but sample sizes were small. These clams survived the spill and subsequent cleanup and may have benefited from reduced competition.
- Poorest growth was the partial 1992 growth of age six and age eight clams at Category 1 sites (Figure 5-3). It should be noted that Category 1 sites include Bainbridge Bight, where growth is obviously poor (see Figure 5-7).
- Although fewer clams were found at the Category 3 sites than at Category 1 or 2 sites, growth rates of individual age classes were generally better than for clams at the Category 1 or 2 sites.
- During the year of the spill (1989), there was little apparent difference in growth rates of clams among categories (Figure 5-6).
- Smaller clams (age zero and one) were not found in sufficient numbers at Category 3 sites to determine 1991 and 1992 growth rates (Figures 5-3 and 5-4).

When clams transplanted from Bainbridge Bight for the four-month experiment at Bainbridge Bight, Block Island, and Northwest Bay West Arm were analyzed, the following trends were noted:

- The 1991 growth period was just beginning at the time of the experiment; virtually no growth (< 0.1 mm) from the previous annulus had occurred prior to calcein marking.
- Best growth occurred at the Category 3 Northwest Bay West Arm site for all four age classes examined (Figure 5-7).
- Worst growth occurred for those clams returned to Bainbridge Bight.
- There was a decrease in mean growth at all sites as clams aged.
- There were no inherent differences in growth of age classes of clams that were transplanted to each of the three sites (Figure 5-8), as shown by 1990 growth when all clams were still in place at the Bainbridge Bight control site.

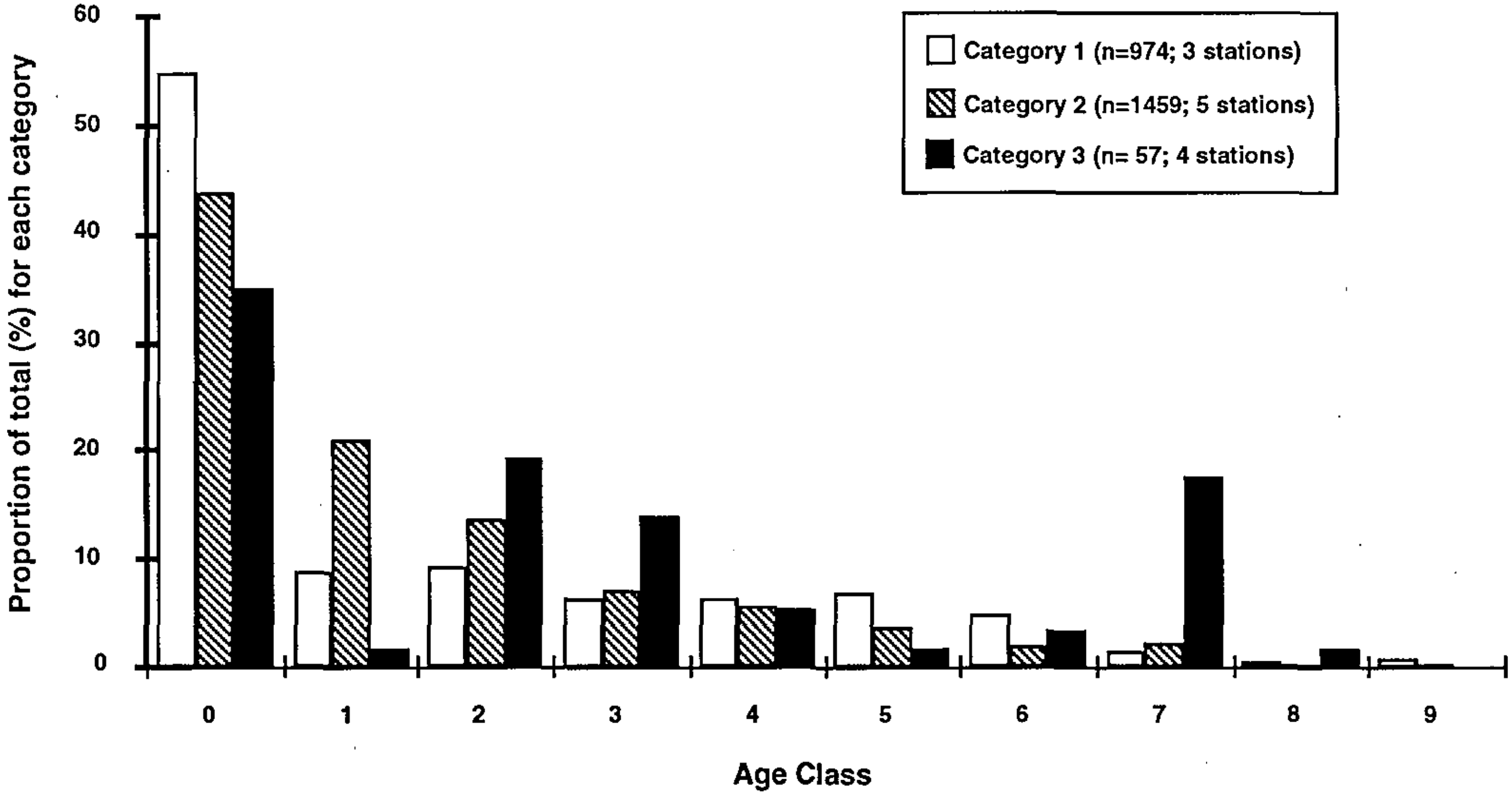

Figure 5-2. Age class distribution of *Protothaca staminea* from core and excavation samples by site category, July 1992.

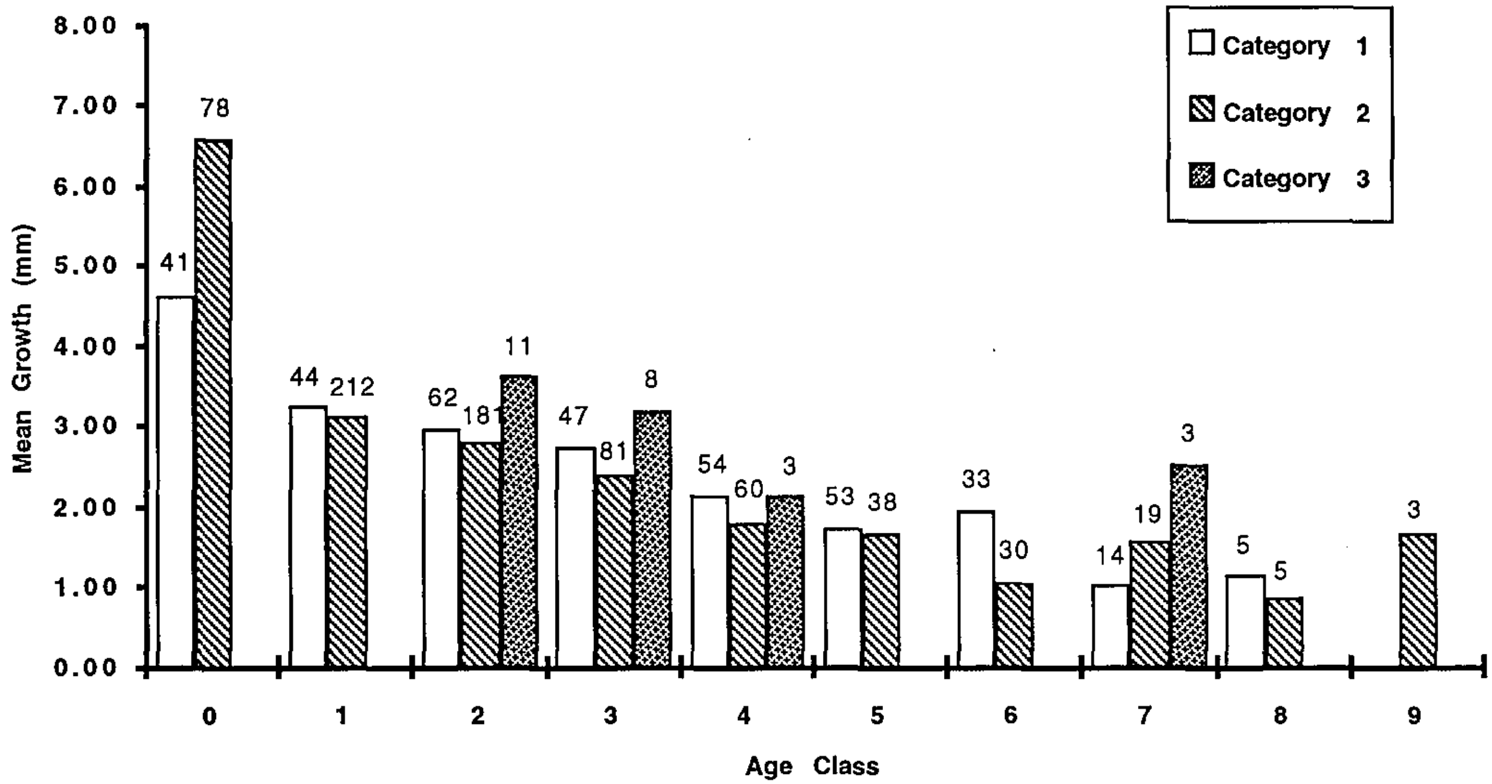

Figure 5-3. Mean growth of *Protothaca staminea* from 0.25 m^2 excavations at lower elevations at three category site groups. Numbers of clams in each age class shown above each bar.

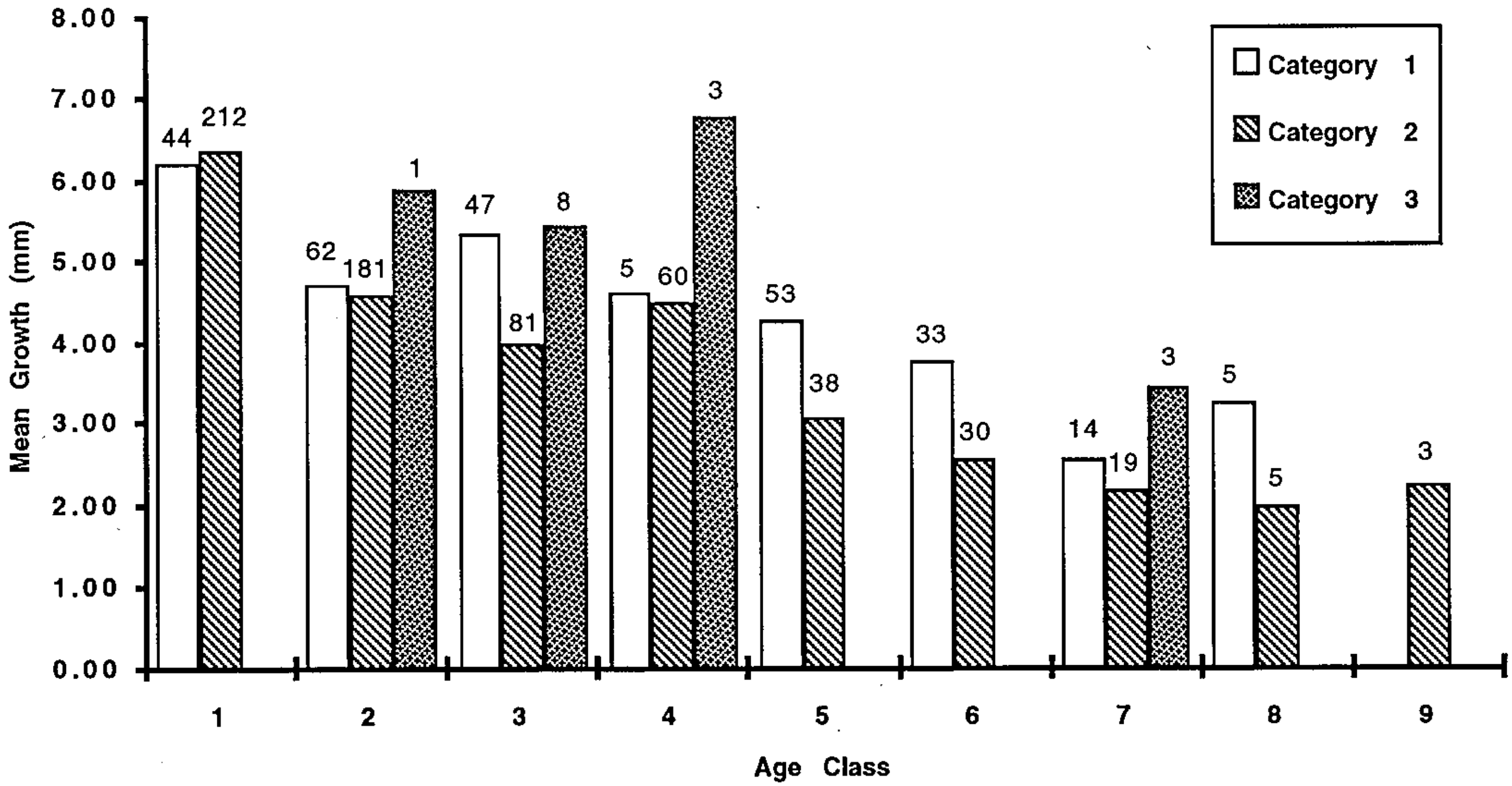

Figure 5-4. Mean 1991 growth of *Protothaca staminea* from 0.25-m^2 excavations of lower elevations by site category. Number measured shown above each bar.

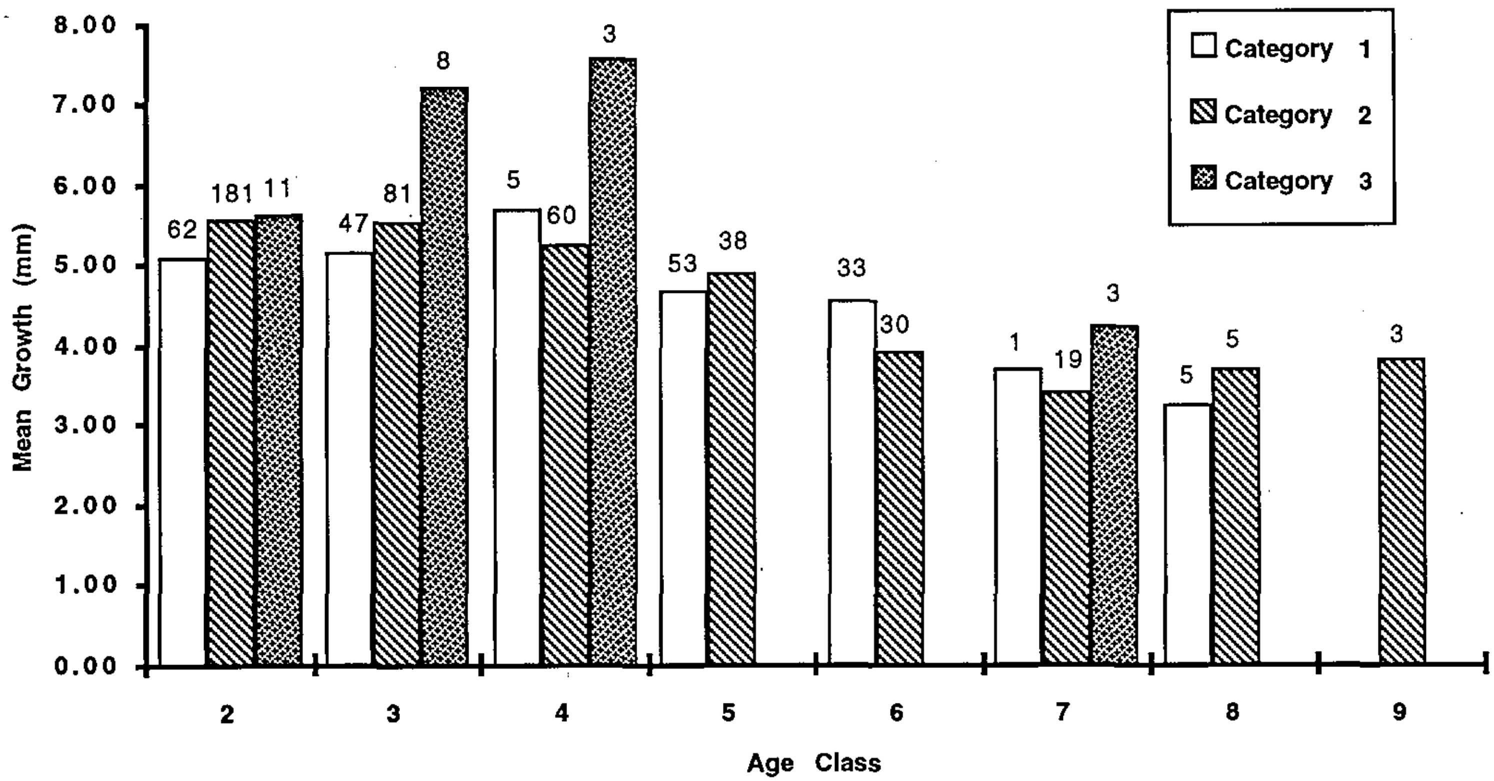

Figure 5-5. Mean 1990 growth of *Protothaca staminea* from 0.25-m^2 excavations of lower elevations by site category. Number measured shown above each bar.

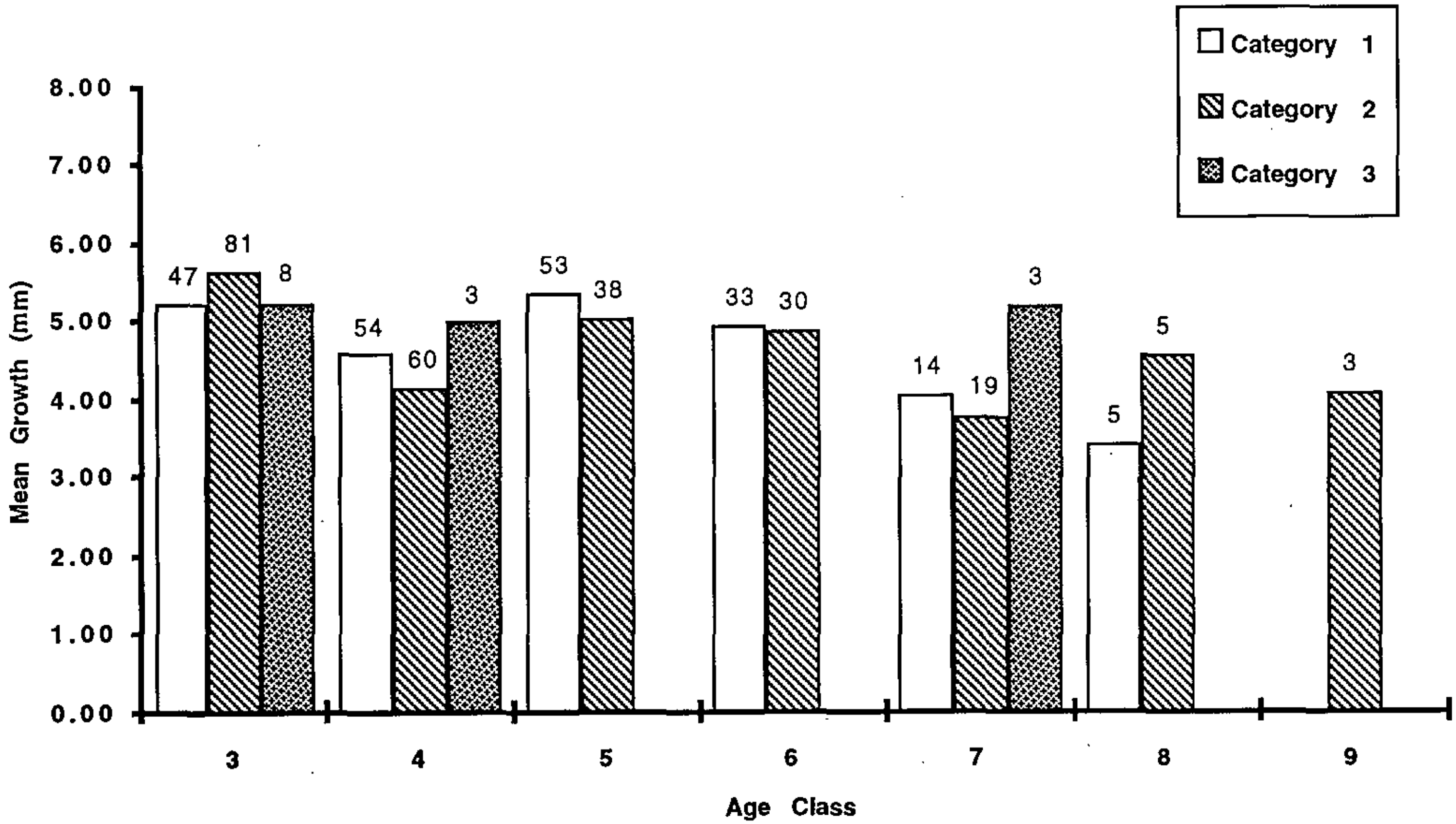

Figure 5-6. Mean 1989 growth of *Protothaca staminea* from 0.25-m^2 excavations of lower elevations by site category. Number measured shown above each bar.

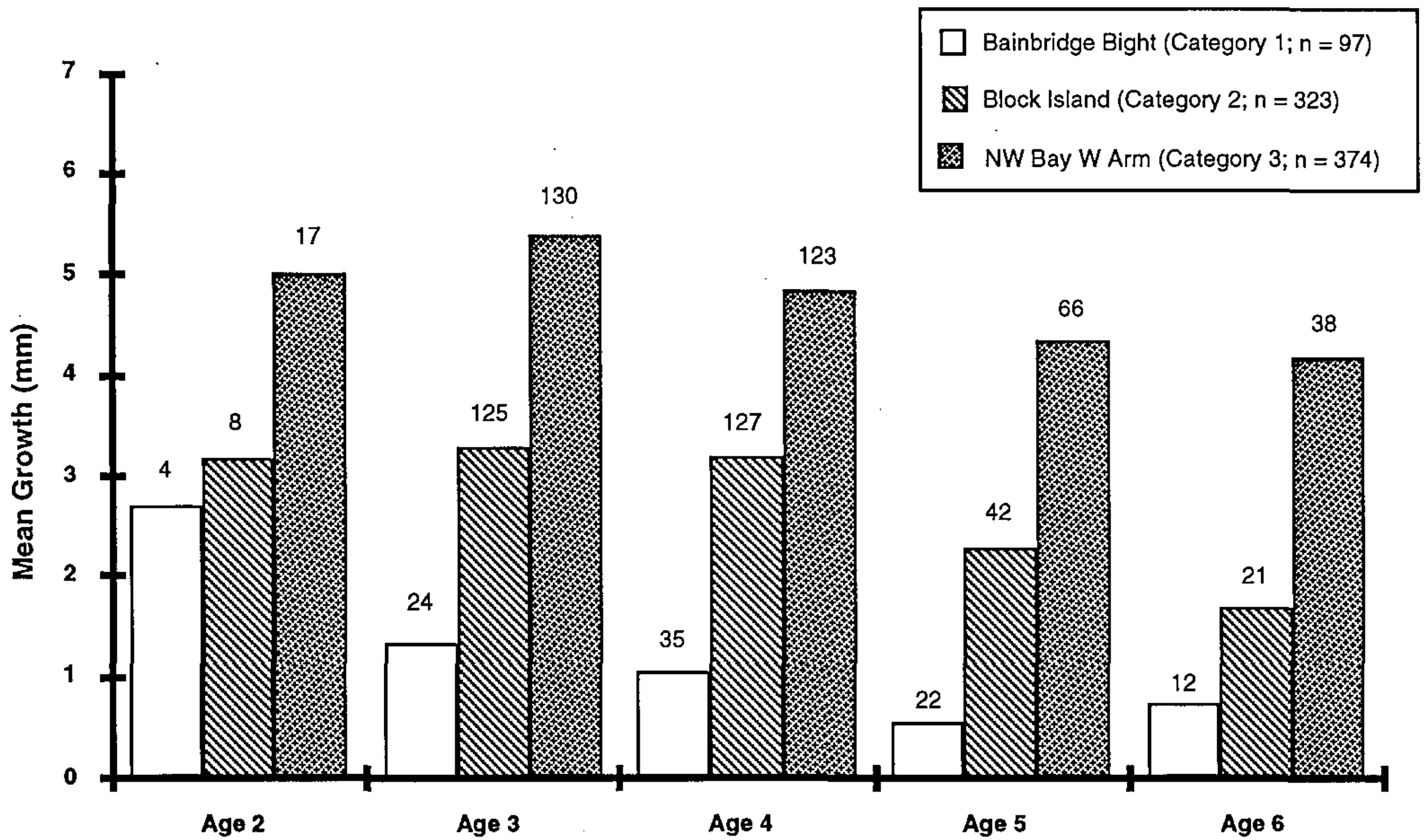

Figure 5-7. Mean growth from May to September 1991 of *Protothaca staminea* at five age classes at three transplant sites; all clams originally removed from Bainbridge Bight. Number measured shown above each bar.

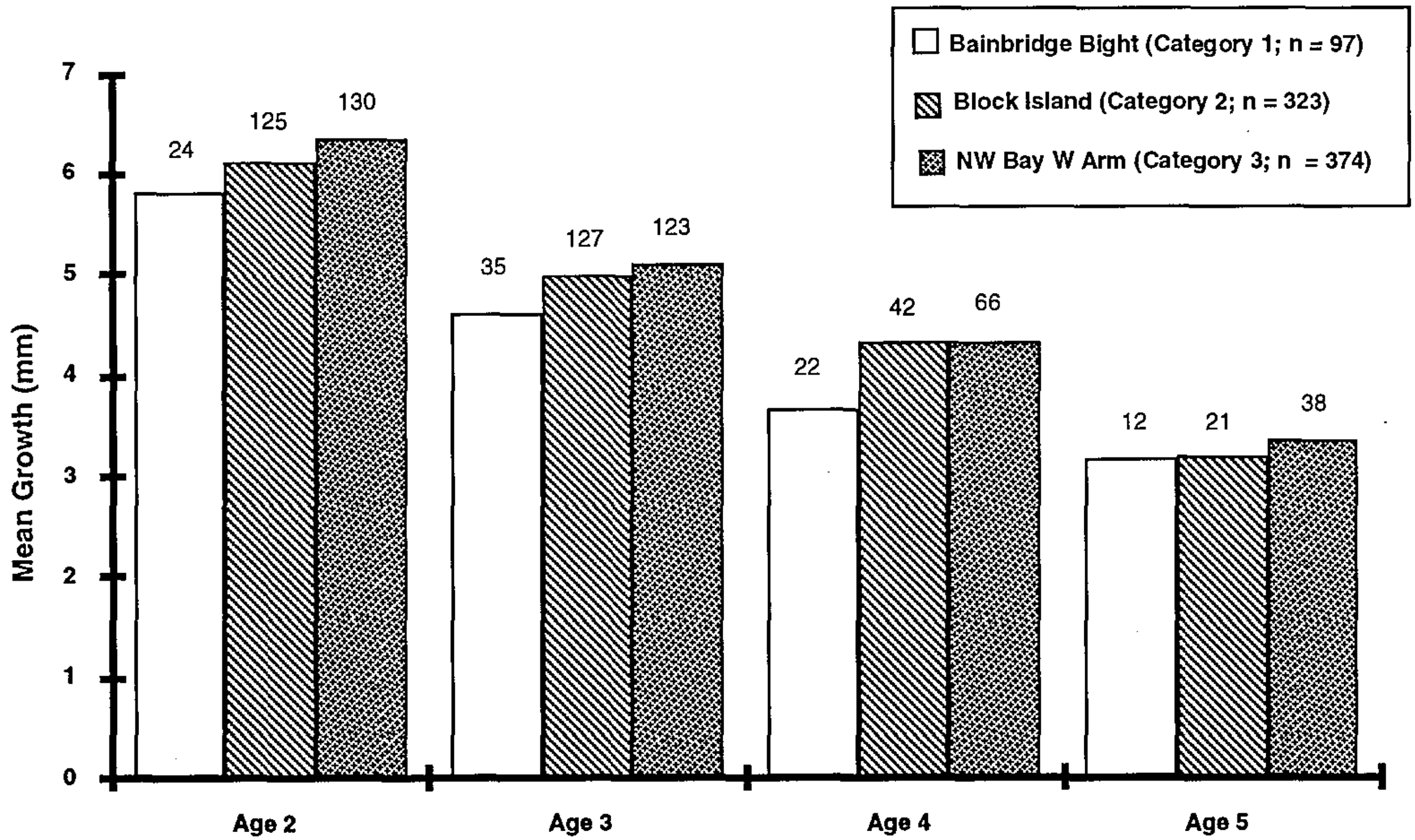

Figure 5-8. Mean 1990 growth of *Protothaca staminea* from source population at Bainbridge Bight. Number measured shown aboe each bar.

The Block Island transplant experiment was examined in greater detail to see if a gradient in hydrocarbons across the site had any effects on growth. Linear regressions of growth of age class three and four clams (Figure 5-9) against sediment PAH showed a strong negative relationship for age three and a lesser relationship for age four clams (age 3: $r^2 = 0.98$, $F = 0.01$; age 4: $r^2 = 0.77$, $F = 0.12$). There also were slight differences in growth of age-class five clams across the hydrocarbon gradient.

DISCUSSION

The littleneck clam (*Protothaca staminea*) was an ideal species to use following a major disturbance such as the *Exxon Valdez* oil spill with its subsequent beach treatment because: it is an abundant and commercially important species; it is long-lived; it is easy to use in growth and aging studies; it may be used in experimental transplant studies; and it readily takes up calcein dye, which shows up as a distinctive check under ultraviolet light.

One concern from oiling and high-pressure hot-water washing of intertidal sand and gravel beaches was the loss of older age classes of this clam from the oiling itself (toxicity), from thermal effects, and/or from washing away of clams and fine-grained sediments. This latter effect of washing (changes in substratum composition) may affect littlenecks' recruitment success.

This species has short siphons and lives three to eight cm below the sediment surface (Morris et al. 1980), so it is highly vulnerable to excavation and burial from high-pressure washing of beaches. In 1989 direct mortalities of *Protothaca* were seen to result from initial oiling (early April) and burial during washing (J. P. Houghton, Pentec Environmental, Inc., personal observation) as well as from thermal or chemical effects of washing (Lees et al., 1990; 1993). Without reproductively mature members of the population present, recruitment to disturbed beaches would be further reduced.

Data from this study indicate that the age-class structure at both Category 2 and Category 3 beaches was substantially altered from age structure seen at Category 1 unoiled sites (Figure 5-2), but clams at sites that were oiled but untreated fared better than those at sites that were oiled and treated. The Category 1 sites show an even distribution of age classes from one to six (i.e., little mortality of established age one and older clams) with a drop in numbers of age-class seven to nine. Clams at the Category 2 sites had higher numbers of age-class zero to three animals and lower numbers of age-class four to nine animals compared to Category 1 sites. This difference may indicate loss of older clams from oiling, with a successful recruitment of animals in the years following the spill.

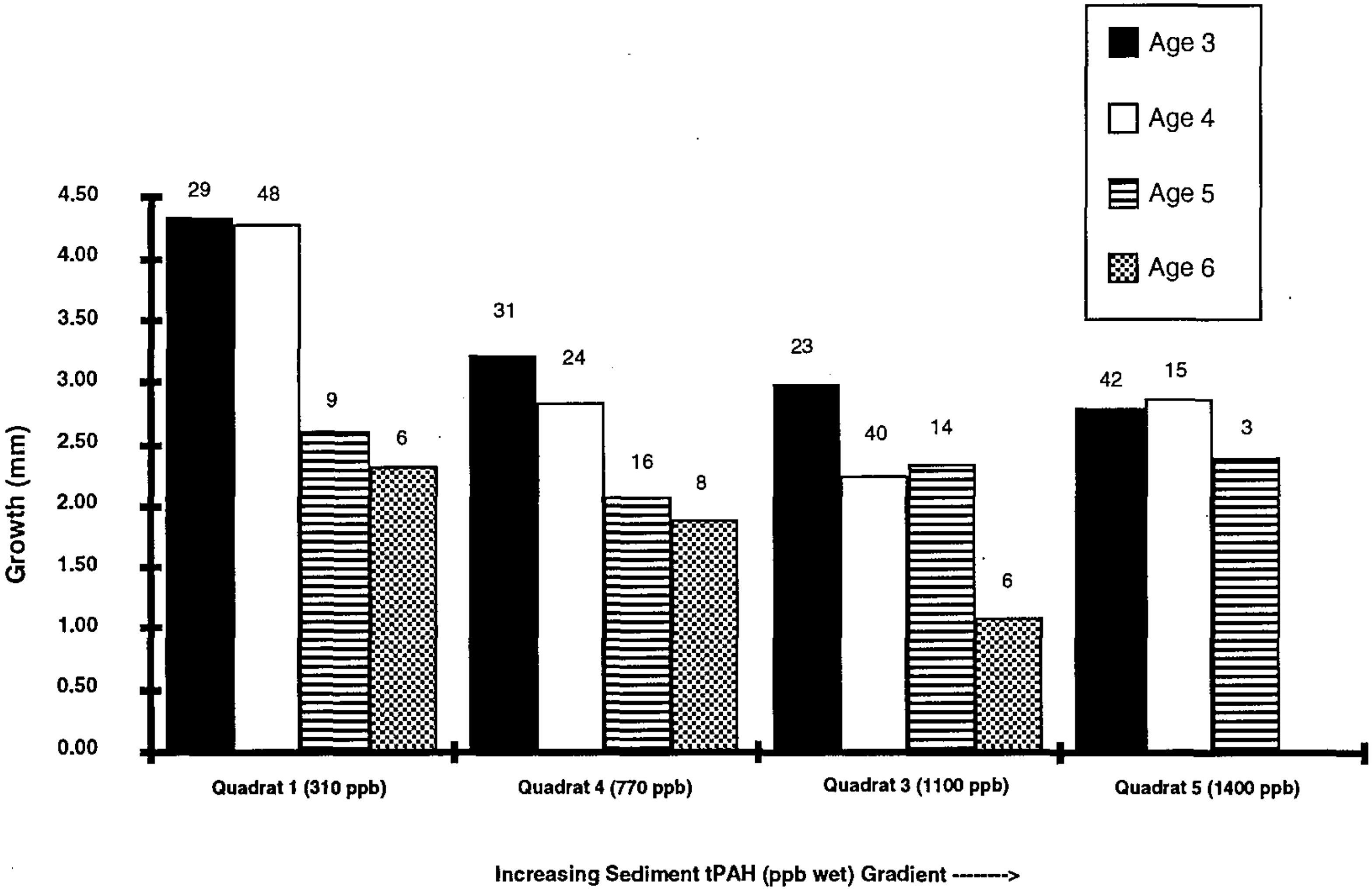

Figure 5-9. Mean growth from May to September 1991 of *Protothaca staminea* (age classes 3-6) transplanted to individual quadrats at Block Island from Bainbridge Bight. Number measured shown above each bar.

Recruitment is highly variable and site dependent (Table 5-2). Other studies have shown that many clam species exhibit variable recruitment; many size/age classes exhibit complete failure (e.g., Paul et al., 1976; Fukuyama and Oliver, 1985). Recruitment is known to be strongly related to several environmental factors including water temperature, food supply, predation, and favorable settlement conditions. Strength of the larval year class available to settle and able to survive determines progression of recovery in affected areas. Category 3 sites had significantly lower abundances of *Protothaca* than the other Category sites (Table 5-1), and there was very low recruitment to these sites (Table 5-2). Clams at these sites that did not die from the effects of oiling were subjected to high-pressure hot-water treatment and were often washed out of the sediments or buried. In addition, the loss of fines and organic matter from these now "sterile" beaches would be unattractive to settling animals. Mean TOC levels at Category 3 sites were lower, although not significantly lower (ANOVA), than at Category 1 or 2 sites (Appendix Table A-6).

Mean growth rates of *Protothaca* varied with age; smaller clams exhibited greater growth (Figure 5-3). Higher growth (in length) for younger animals is generally the case in bivalves (e.g., Paul et al., 1976, Cerrato, 1980). Growth rates ranging from about 1.0 mm per year in clams aged seven and eight to more than 6.0 mm per year in age-zero clams are similar to the growth rates of 2 to 5 mm per year found for various age classes in eastern Prince William Sound by Feder and Paul (1973). Although there were fewer clams at the Category 3 sites, those left were growing at higher rates than at Category 1 or 2 sites (Figures 5-3 through 5-6). Higher growth rates were also seen in animals transplanted to the Northwest Bay West Arm Category 3 site (Figure 5-7). These higher rates at this site may be due to somewhat warmer water temperatures in this protected cove or to reduced competition for food resources that resulted from the widespread cleaning in Northwest Bay.

Relatively low growth rates were seen in clams transplanted back to the Category 1 Bainbridge Bight site. These lower rates may be due to the artifact that these animals were held in calcein dye (out of the sediment) for several days longer than other transplanted animals. Another reason may be the transplant location of these animals. Bainbridge Bight lies at the south end of Bainbridge Pass near the Bainbridge Glacier; water temperatures there were consistently the coldest of any in this study (Appendix A-4), a factor that would certainly contribute to slower growth. Also, tidal levels on the day of transplanting were higher than they were when the clams were originally collected; thus, clams had to be replanted at a higher tidal level than that from which they were dug. This change in elevation may have effected the growth rate because there would be less immersion time and, subsequently, less time to feed. The higher mortalities of these clams compared to the other transplanted clams (Houghton et al., 1993) also indicate that these clams were stressed or were in poor habitat or that the time out of sediment effected their survival.

Growth rates of clams transplanted to the heavily oiled Block Island Category 2 site were lower for all age classes (Figure 5-8) than for clams transplanted to the Category 3 site, which had relatively low sediment hydrocarbons. In addition, all age classes of clams at Block Island had a higher growth rate than those at the Category 1 site. These effects cannot be attributed to site oiling, however, because no site replication was done. When growth rates in the four individual quadrats at Block Island were examined, increasing PAHs had a negative effect on growth of age three and four clams but little effect on age five and six clams (Figure 5-9).

This indication of retarded growth of clams in more heavily oiled areas is consistent with the pattern of reduced survival noted for the same group of transplanted clams across the same gradient (Houghton et al., 1993). Remarkably, this same Block Island lower station has had the highest rate of recruitment of *Protothaca* of any site in this study (e.g., Table 5-2) and had the highest density of larger clams sampled in 1992 (Table 5-1). Another oiled Category 2 site (in Bay of Isles; not sampled in 1992) had a higher density of littlenecks than Block Island in 1991 (Houghton et al., 1993). The 1992 clam transplant experiment is expected to provide more insight into effects of hydrocarbons on survival and growth rates of *Protothaca*.

CHAPTER 6

SPECIAL STUDIES

INTRODUCTION

This chapter describes the results from several special studies done in conjunction with the basic monitoring program described in Chapters 2 through 5 to enhance understanding of the effects of oiling and treatment on individual taxa or areas where treatment methods may have varied.

EELGRASS SAMPLING

Methods

Field

In 1991 eelgrass (*Zostera marina*) plants and seeds were cross-transplanted between Category 1 and 3 sites to examine differences in long-term clonal growth rates and seed germination. The growth experiment was performed at two Category 1 sites (Bass Harbor and Stockdale Harbor) and two Category 3 sites (Sleepy Bay and Northwest Bay). The germination experiment was performed at only Bass Harbor and Sleepy Bay. Site selection was based on maximum differences in PAH concentrations between sites with similar physical conditions.

Growth Rate Experiment

Divers collected 100 eelgrass plants (shoots plus rhizomes) at each of the four sites. Immediately after collection the plants were transported in seawater-filled buckets to a laboratory, where epiphytes were removed and wet weight for each individual plant was recorded. Each plant was tagged with an individually numbered zip-tag around the most recent plastochrone interval. Plants from the same locations were then tied together loosely in bundles of five to prevent damage to the rhizomes. Each bundle was placed in seawater and kept cold and dark until planting. Transplanting was completed within 24 hours of collection. Five bundles (25 plants) from each site were transplanted at each of the four growth study sites. Thus, 100 plants were transplanted at each site.

In July 1992 the surviving plant bundles were collected from all sites except Stockdale Harbor. The plant bundles were untied, and each plant was weighed in the same manner as in 1991. Because eelgrass has a herbaceous perennial growth cycle, it was assumed that wet-weight changes were a function of rhizomal growth and not differences in shoot growth. Despite an extensive search, the transplant site at Stockdale Harbor was not relocated.

Seed Germination Experiment

In July 1991 sediments from Bass Harbor (Category 1) and Sleepy Bay (Category 3) were collected and placed in shallow four-ounce germination containers. Twenty-five containers were prepared with each sediment. The containers were distributed between sites so that 15 contained local sediment and 10 contained sediment from the other site. Ten containers were placed at the upper and lower edges of the eelgrass bed, and five containers were placed in the middle of the bed.

In September 1991 ripe seeds were collected from Bass Harbor and Sleepy Bay and planted in the germination containers. Twenty seeds were planted in each container so that, at both sites, five containers contained Bass Harbor seeds in Bass Harbor sediment, five contained Sleepy Bay seeds in Bass Harbor sediment, five contained Sleepy Bay seeds in Sleepy Bay sediment, and five contained Bass Harbor seeds in Sleepy Bay sediment. The remaining five containers held local sediment without seeds. Distribution of the seed/sediment combinations is shown in Table 6-1.

In July 1992 divers collected the germination containers and placed them in individual Ziploc bags. On board the support vessel the containers were examined for germinated seeds, and the seeds remaining were counted after the sediment was sieved through a 0.5-mm screen.

EELGRASS RESULTS

Growth and Survival of Transplanted Eelgrass Plants

Transplanted bundles were recovered in 1992 from all of the transplant sites except Stockdale Harbor. Overall, we recovered and recorded whole wet weight for 28 percent of the tagged eelgrass plants at these sites. Many more healthy plants were recovered in the transplant bundles, but these were not processed because their tags were missing.

Sediment quality at the study sites appeared to exert an influence on growth and survival of the transplanted plants. On average, plants transplanted to Bass Harbor survived better than those transplanted to Northwest Bay or Sleepy Bay (Table 6-2). Average increases in wet weight were greatest on real and relative bases at Northwest Bay. In contrast, average weight decreased appreciably at Sleepy Bay (-22 percent overall) for plants from all source sites (Table 6-2); fewer than half as many plants increased in weight as at the other two sites. Four of the plants recovered at Bass Harbor had developed flowering stalks, but no flowering stalks were observed in plants recovered at Northwest Bay or Sleepy Bay. Thus, it appears that site characteristics influence growth and survival and may affect development of reproductive stalks.

Table 6-1. The number and combination of germination containers* transplanted at two eelgrass beds of different categories in Prince William Sound.

Source		Transplant location					
		Bass Harbor			Sleepy Bay		
Sediment	Seed	Upper	Middle	Lower	Upper	Middle	Lower
Category 1	Bass Harbor`	2	1	2	2	1	2
Bass Harbor	Sleepy Bay	2	1	2	2	1	2
	None	2	1	2	0	0	0
Category 3	Bass Harbor	2	1	2	2	1	2
Sleepy Bay	Sleepy Bay	2	1	2	2	1	2
	None	0	0	0	2	1	2
	Total	10	5	10	10	5	10

Plants from the different source sites exhibited substantially different changes in survival and whole wet weight. Plants from Sleepy Bay had highest survival, whereas those from Northwest Bay survived relatively poorly. Survival rates of the plants did not appear to be influenced by the treatment category of the source site. Plants from Bass Harbor had the highest average increase in whole wet weight, but plants from Northwest Bay exhibited greatest percent increase. Plants from Sleepy Bay exhibited relatively poor increases in weight on real and relative bases (Table 6-2). Real weight gain appeared to be higher in plants from Category 1 sites, but relative rates did not appear to be influenced by the treatment category of the source site.

Seed Germination Study

Recovery of germination containers from both Sleepy Bay and Bass Harbor was poor in 1992 (Table 6-3). No germination containers were recovered from the upper edges of the beds at either Sleepy Bay or Bass Harbor. Eight germination containers were recovered from the lower edges of both beds. Four of five were recovered from the middle of the bed at Bass Harbor, but none were recovered from the middle of the Sleepy Bay bed.

This experiment produced no useful information. None of the seeds planted in the germination containers had germinated. Only three of the 360 seeds planted in the recovered containers were found after sieving.

Table 6-2 Weight gain and survival of plants during the eelgrass transplant study at four locations in Prince William Sound, 1991 to 1992.

Study site	Origin of plants	No. of plants recovered*	Percent survival	Average wet weight change (g wet weight)	SE	Average percent change	SE	No. of plants showing weight gain	Average percent plants showing weight gain
Sorted by study site									
Bass Harbor	Bass Harbor	6	24	5.62	1.65	97	37	6	73
1.8 ppb**	Northwest Bay	4	16	4.35	2.74	98	60	3	
Category 1	Stockdale Harbor	10	40	2.28	2.33	31	37	5	
	Sleepy Bay	13	52	4.09	1.98	33	33	10	
	Mean in Bass Harbor sediment		36	3.57		54		6	
Northwest Bay	Bass Harbor	7	28	10.10	4.26	124	51	7	70
120 ppb	Northwest Bay	3	12	5.67	7.35	241	83	2	
Category 3	Stockdale Harbor	5	20	8.92	4.29	108	34	4	
	Sleepy Bay	8	32	0.23	3.50	18	27	3	
	Mean in Northwest Bay sediment		21	4.94		122		3	
Sleepy Bay	Bass Harbor	5	20	-1.48	3.51	-21	29	2	30
160 ppb	Northwest Bay	6	24	-3.80	3.08	-13	16	2	
Category 3	Stockdale Harbor	8	32	-2.93	2.06	-20	10	2	
	Sleepy Bay	8	32	-3.80	2.05	-34	10	2	
	Mean in Sleepy Bay sediment		29	-3.51		-22		2	

Table 6-2 Weight gain and survival of plants during the eelgrass transplant study at four locations in Prince William Sound, 1991-92.

Study site	Origin of plants	No. of plants recovered*	Percent survival	Average wet weight change (g wet weight)	SE	Average percent change	SE	No. of plants showing weight gain	Average percent plants showing weight gain
Sorted by plant origin									
Bass Harbor	Bass Harbor	6	24	5.62	1.65	97	37	6	83
Northwest Bay		7	28	10.10	4.26	124	51	7	
Sleepy Bay		5	20	-1.48	3.51	-21	29	2	
	Mean for Bass Harbor plants		24	4.75		67		5	
Bass Harbor	Northwest Bay	4	16	4.35	2.74	98	60	3	54
Northwest Bay		3	12	5.67	7.35	241	83	2	
Sleepy Bay		6	24	-3.80	3.08	-13	16	2	
	Mean for Northwest Bay plants		17	2.07		109		2	
Bass Harbor	Sleepy Bay	13	52	4.09	1.98	33	33	10	52
Northwest Bay		8	32	0.23	3.50	18	27	3	
Sleepy Bay		8	32	-3.80	2.05	-34	10	2	
	Mean for Sleepy Bay plants		39	0.17		6		5	
Bass Harbor	Stockdale Harbor	10	40	2.28	2.33	31	37	5	48
Northwest Bay		5	20	8.92	4.29	108	34	4	
Sleepy Bay		8	32	-2.93	2.06	-20	10	2	
	Mean for Stockdale Harbor plants		31	2.76		40		4	

* 25 plants deployed from each source; 100 at each study site.

** Total PAH concentration in sediment at each study site (ppb) in 1991.

Table 6-3 Success in seed germination between September 1991 to July 1992, Prince William Sound.

	Seeds			Germination containers		
Location	Source of sediment	Source of seeds	Number recovered	Location	Area of bed	Number recovered
Sleepy Bay (deep)*	Sleepy Bay	Sleepy Bay	1			
	Bass Harbor	Sleepy Bay	0	Sleepy Bay	Upper	0/10
	Bass Harbor	Bass Harbor	0		Mid	0/5
	Sleepy Bay	Bass Harbor	0		Lower	8/10
Bass Harbor (mid)**	Bass Harbor	Bass Harbor	0	Bass Harbor	Upper	0/10
	Sleepy Bay	Sleepy Bay	0		Mid	4/5
					Lower	8/10
Bass Harbor (lower)*	Bass Harbor	Sleepy Bay	1			
	Bass Harbor	Bass Harbor	1			
	Sleepy Bay	Bass Harbor	0			
	Sleepy Bay	Sleepy Bay	0			
Bass Harbor (upper)	Bass Harbor	None	0			

* 40 seeds deployed from each source.
** 20 seeds deployed from each source.

Discussion

Following the *Exxon Valdez* oil spill and subsequent cleanup activities, a major concern has been how increased subtidal sediment hydrocarbon levels have affected the subtidal biota in Prince William Sound. Since 1989 eelgrass has been used as an indicator species to assess the subtidal community health (e.g., Teas et al., 1991). In this study, we examined the effect of total PAHs in the sediment on eelgrass survival and growth. Plants were transplanted within and between Category 1 (Bass and Stockdale harbors) and Category 3 sites (Northwest and Sleepy bays) with 1991 average concentration of total PAHs in sediment of 1.6 and 140 ppb, respectively (Houghton et al., 1993).

The transplant experiment appears to have been successful. A large proportion of the transplant bundles were still in place and growing when we returned to recover the bundles in 1992. We successfully recovered and identified 28 percent of the transplanted plants. Average shoot length of the transplants did not appear to have changed appreciably over the period of the experiment. Many of the transplanted rhizomes had more plastochrone intervals at the time of recovery then when they were transplanted. Finally, only one of the transplant bundles recovered had total mortality.

Bass Harbor, Sleepy Bay, and Stockdale Harbor eelgrass beds appeared to have fairly similar physical characteristics; the inside (shoreward) edge of the bed in each location was about three m below mean lower low water (MLLW), and the sediment was mainly sand. Northwest Bay was shallower (one m below MLLW), and the sediment was a mixture of mud, gravel, and cobble. Biomass estimates based on shoot length and rhizome dry weight showed that Northwest Bay produced shorter plants with smaller rhizomes (Houghton et al., 1991; 1993).

The null hypotheses were that plant survival and growth (i.e., increase in wet weight) would not differ between Category 1 and Category 3 sites. We also expected plants transplanted between physically similar sites would exhibit similar growth rates (wet-weight gains). The results do not support either the hypothesis or the expectation, however.

With one exception, transplants from the Category 1 sites (Bass and Stockdale Harbors) had the greatest increases in wet weight at all sites. At Bass Harbor, however, plants transplanted from Northwest Bay grew faster than transplants from Sleepy Bay and Stockdale Harbor. Also, both Category 3 transplants outperformed plants from Stockdale Harbor. Although Category 3 plants outperformed plants from Stockdale Harbor on average, Category 3 plants did not outperform Category 1 plants.

Transplants to Sleepy Bay did not perform as well as plants transplanted to the Category 1 sites. On average, wet weight of transplants to Sleepy Bay decreased more than 20 percent. Increases were observed in only 30 percent of the plants recovered from Sleepy Bay, whereas wet weight increased in 70 and 73 percent of the plants recovered from Northwest Bay and Bass Harbor, respectively. Also, although physical and biological characteristics are reasonably similar at Bass Harbor (Category 1) and Sleepy Bay (Category 3), transplants at Bass Harbor outperformed transplants at Sleepy Bay by substantial margins in both average weight gain per plant and percent gain and in number of plants gaining. Because plants from all source sites exhibited poor performance, it appears that some factor (e.g., sediment hydrocarbon levels or type of treatment) is affecting eelgrass growth in Sleepy Bay.

Although all plants grew poorly at Sleepy Bay, Category 1 transplants grew better at the other Category 3 site (Northwest Bay) than at Bass Harbor, the Category 1 site. Plants from Sleepy Bay grew substantially less and had lower percent change in wet weight than plants from other sites (Table 6-2). Based on the documented differences in plant biomass and because of the differences in physical characteristics, we expected plants from the sandy sites (Bass Harbor, Stockdale Harbor, and Sleepy Bay) to perform poorly at Northwest Bay. In fact, only plants from Sleepy Bay performed poorly. Sleepy Bay plants were the poorest performers, even at Sleepy Bay. This combination of observations suggests that plants from Sleepy Bay were in poor physiological condition and that the condition is cumulative and persistent.

In summary, the purpose of the eelgrass transplant study was to examine the relationship between increased hydrocarbon concentrations in eelgrass beds and growth and survival of eelgrass plants. Because the transplants at Stockdale Harbor were not relocated, there is no replication in Category 1, and the hypothesis therefore cannot be tested statistically. In addition, the sample size (number of plants recovered) is small, and the variance of the data is high (Table 6-2). Nevertheless, the study suggests some interesting patterns. At Sleepy Bay transplants from all source sites exhibited poor performance, and Sleepy Bay plants performed poorly at all sites; however, it is possible that eelgrass growth is in some way affected at Sleepy Bay.

BLOCK ISLAND QUALITY ASSURANCE SAMPLING

Methods

Six quadrats from the middle elevation station at Block Island were sampled by two different pairs of observers to assess differences in observer enumeration. Resampling occurred eight days after the initial sampling. Mean abundances for all taxa were compared across the six quadrats and were similar in most cases (Appendix Table A-7).

Results

The mean difference in abundance of *Fucus* between observers was about three percent cover. The encrusting red alga *Hildenbrandia rubra* differed by one percent cover, and all other taxa differed by less than one percent. For sessile animals differences in mean abundance between observers was greatest in the barnacle *Semibalanus balanoides* (eight percent cover difference), and *Mytilus* differed by about two percent cover. Motile animals would be expected to differ in counts between observers since enumerations were done about a week apart; littorines, however, differed by only between seven and ten percent. The largest difference was in *Lottia pelta*, which differed by 15.5 percent; this difference may be partly attributable to uncertainties in field identifications of limpets. When all limpets were lumped into the family Lottiidae (as was done for all analyses) the difference dropped to about six percent.

Abundances in individual quadrats were also examined. *Fucus* estimates were found to differ by as much as 15 percent cover in the two estimates for one quadrat, but in three of the quadrats there was no difference. *Semibalanus balanoides* differed by 5 to 20 percent cover and *Mytilus* varied from 1 to 13 percent cover. *Littorina scutulata* numbers showed the greatest difference from 12 to 190 individuals, and *L. sitkana* differed from 0 to 72 in counts. The lumped Lottiidae differed in individual quadrats by 1 to 13 animals. These differences may be due to differences in precise orientation of the quadrats (for cover estimates), movement of motile organisms, the first observer's practice of physically setting aside each individual littorine as it was counted, and/or real differences in observation techniques.

Discussion

The average error rate between the first and second observations of quadrats at Block Island is small and within expected station variance given minor differences in quadrat positioning and the observational techniques of the scientists sampling each quadrat. Between-observer variance in the results of quadrat sampling does not appear to be a significant source of bias in this study.

NORTHWEST BAY WEST ARM ROCKY STUDIES

From May through early September 1989, a substantial effort was expended throughout the Knight Island group to treat oiled shorelines with high-pressure hot-water washes. Although nearly all of the designated segments of the Northwest Bay West Arm shoreline were listed in official records as having been treated in such a fashion, on a smaller scale the actual treatment intensity was less consistent because of difficulties deploying equipment, varying tides, and other operational factors. According to on-scene observations during the summer of 1989, this variability was not uncommon in that area (P. Montesano, Alaska Department of Environmental Conservation, personal communication.; J. P. Houghton, Pentec Environmental, Inc., personal observation).

In late 1989 (Houghton et al., 1990b) and 1990 (this study), many areas were noted along the straight, steeply sloping rocky shorelines of Northwest Bay, where biota had been mostly removed and areas of nearly bare rock were exposed; the condition was similar to that at the Northwest Bay Rocky Islet study site. Sharp vertical boundaries often separated these severely affected areas from adjacent rocky areas supporting a much richer biota and a near normal cover of rockweed, barnacles, and mussels (see Figure F-1 in Houghton et al., 1993). Because the 1989 oiling was likely continuous across these relatively smooth rocky faces and because there are no natural reasons for the vertical boundaries, the differences can be assumed to reflect differing degrees of severity of treatment.

One such area was sampled in 1989 under an Exxon-sponsored study (Houghton et al., 1990b) and was resampled in 1991 and 1992 as the Northwest Bay West Arm rocky sites. Both a Category 3, heavily treated middle elevation station (left side of photographs in Figure F-1 in Houghton et al., 1993) and an adjacent reference station (right side of photographs) were sampled. The reference station appeared in September 1989 and in July 1990 to have a normal assemblage of biota characteristic of this habitat and elevation and was assumed (Houghton et al., 1990b) to have experienced a lesser degree of treatment if it was treated at all. Because the assemblages on the two immediately adjacent sites can be assumed to differ primarily in the severity of treatment, it is hypothesized that as recovery occurs on the Category 3 station, the number of significant differences between the two stations will decrease. When no significant differences remain in any measured variable, the Category 3 station can be said to have recovered.

Oil was present only on the heavily treated site in September 1989 (Houghton et al., 1990b) and has not been visible on either side of the vertical boundaries since 1990. This pattern indicates that on this substratum, the less severe treatments were as at least as successful at removing oil as were the more severe treatments applied to the Category 3 site.

Methods

The middle elevations at the paired (side-by-side) Category 3 and reference sites on the rock face in the West Arm of Northwest Bay (see Figure F-1 in Houghton et al., 1993) were resampled at previously marked quadrats on June 27, 1992. The data from the Category 3 site have been used in the pooled data for that category discussed in Chapter 3. The reference site data were not included in the Chapter 3 presentations because the nature of treatments that may have been applied to this area can not be ascertained. It is clear from 1989 observations and sampling (Houghton et al., 1990b) that this site was either not treated at all or treated with nonintrusive (i.e., low-pressure low-temperature) washes.

The five quadrats sampled at each of the two sites (middle stations) were used as replicates in randomization t-tests (Chapter 3) to compare key variables.

Results

Abundances of several taxa remained significantly different between the two sites in 1992 (Table 6-4). Rockweed sporelings ($p = 0.079$) and the red algae *Halosaccion glandiforme* ($p = 0.007$) were more abundant at the reference station and several other red algae found at that station (*Cryptosiphonia woodii, Neorhodomela larix, Mastocarpus papillatus*) were not found at the Category 3 site. There was no significant difference in the abundance of mature rockweed between the two stations (65 percent cover at the Category 3 station versus 85 percent at the reference station). Mean total algal cover ($p = 0.008$) and mean number of algal taxa were both greater at the reference station (121.2 percent and 12.2 taxa versus 74.1 percent and 4.8 taxa, respectively).

Littorine snails were far more abundant at the Category 3 station; *L. scutulata* density was 312.8 there as opposed to only 10.2 at the reference station ($p = 0.0159$). The hermit crab *Pagurus hirsutiusculus* and the pulmonate *Siphonaria thersites* were both significantly more abundant at the reference station ($p = 0.067$ and 0.008, respectively). Finally, the mean number of animal taxa was greater at the reference station (12.6 versus 9.8).

Table 6-4 Northwest Bay West Arm, rocky middle intertidal epibiota, 1991-92 (* = p < 0.10; ** = p < 0.05; *** = p < 0.01).

	1991				1992				1991-1992 Percent Change	
Taxon	Category 3 average	Reference average	Difference (percent)	t-test	Category 3 average	Reference average	Difference (percent)	t-test	Category 3 (percent)	Reference (percent)
Algae										
Acrosiphonia spp.	2.00	1.20	66.67	0.7222	0.50	1.50	-66.67	0.4823	-75.00	25.00
Cryptosiphonia woodii	0.00	0.40	-100.00	1.0000	0.00	1.20	-100.00	0.1672	-	200.00
Elachista fucicola	0.10	3.80	-97.37	0.0476 **	0.00	0.40	-100.00	0.1661	-100.00	-89.47
Encrusting coralline algae	0.20	4.60	-95.65	0.2222	0.20	2.70	-92.59	1.0000	0.00	-41.30
Encrusting red algae	9.40	18.00	-47.78	0.6587	1.10	10.20	-89.22	0.0242 **	-88.30	-43.33
Enteromorpha intestinalis	0.30	0.00	-	0.1667	0.00	0.00	-	1.0000	-100.00	
Fucus gardneri	34.40	88.00	-60.91	0.0079 ***	63.00	85.00	-25.88	0.3542	83.14	-3.41
Fucus gardneri (sporelings)	2.40	2.40	0.00	1.0000	0.20	0.80	-75.00	0.0789 *	-91.67	-66.67
Gloiopeltis furcata	7.20	0.70	928.57	0.0159	4.60	2.50	84.00	0.1856	-36.11	257.14
Halosaccion glandiforme	0.00	2.10	-100.00	0.0476 **	0.00	1.00	-100.00	0.0069 ***	-	-52.38
Mastocarpus papillatus	0.00	1.40	-100.00	0.0476 **	0.00	1.00	-100.00	0.1600	-	-28.57
Melanosiphon intestinalis	0.50	0.50	0.00	1.0000	0.10	0.20	-50.00	1.0000	-80.00	-60.00
Monostroma grevillei	0.20	0.60	-66.67	0.5635	0.00	0.20	-100.00	1.0000	-100.00	-66.67
Neorhodomela larix	0.10	5.60	-98.21	0.1667	0.00	6.10	-100.00	0.4527	-100.00	8.93
Neorhodomela oregona	3.40	11.40	-70.18	0.1032	2.40	5.20	-53.85	0.4014	-29.41	-54.39
Pilayella littoralis	0.10	8.40	-98.81	0.0476 **	0.80	1.40	-42.86	0.6854	700.00	-83.33
Soranthera ulvoidea	1.00	0.20	400.00	1.0000	0.00	0.10	-100.00	1.0000	-100.00	-50.00
Total algal coverage	61.80	149.40	-58.63	0.0079 ***	74.10	121.20	-38.86	0.0080 ***	19.90	-18.88
Number of taxa	7.00	10.60	-33.96	0.1111	4.80	12.20	-60.66	0.9745	-31.43	15.09
Animals										
Anthopleura spp.	0.00	0.40	-100.00	0.4444	0.00	0.60	-100.00	0.4345	-	50.00
Semibalanus balanoides (%) adult + set	18.90	0.70	2600.00	-	11.40	0.90	1166.67	0.0442 **	-39.68	28.57
Chthamalus dalli (%) adult + set	15.50	23.60	-34.32	-	12.60	9.20	36.96	0.2974	-18.71	-61.02
Littorina scutulata	312.80	10.20	2966.67	0.0159 **	433.60	12.20	3454.10	0.0067 ***	38.62	19.61
Littorina sitkana	11.60	62.60	-81.47	0.0873 *	83.80	6.20	1251.61	0.3130	622.41	-90.10
Lottiidae, unid.	22.40	47.00	-52.34	0.4444	42.20	45.00	-6.22	0.8988	88.39	-4.26
Mytilus edulis (%) adult + spat	0.50	0.40	25.00	1.0000	0.90	2.50	-64.00	0.4398	80.00	525.00
Nucella lamellosa	0.60	7.00	-91.43	0.0079 ***	14.60	7.20	102.78	0.3712	2333.33	2.86
Pagurus granosimanus	0.40	0.00		0.4444	0.00	0.20	--100.00	1.0000	-100.00	-
Pagurus hirsutiusculus	1.80	11.20	-83.93	0.0159 **	2.80	7.80	-64.10	0.0665 *	55.56	-30.36
Siphonaria thersites	0.20	21.20	-99.06	0.0079 ***	3.20	63.20	-94.94	0.0078 ***	1500.00	198.11
Number of individuals	349.80	159.60	119.17	0.3889	581.00	143.00	306.29	0.0267 **	66.09	-10.40
Number of taxa	6.60	7.80	-15.38	0.1984	9.80	12.60	-22.22	0.0248 **	48.48	61.54

Discussion

The two Northwest Bay West Arm sites were first sampled in September 1989 (Houghton et al., 1990b). The following descriptions are extracted from that report:

> "The rocky substrate of the [middle] intertidal untreated [reference] area was dominated by a thick cover of rockweed (87.5-percent cover) and two red algae (*Neorhodomela larix*, 6.25 percent; *Odonthalia* sp., 8.25 percent). Barnacles (*Chthamalus dalli*, 9.25-percent cover), predatory snails (*Nucella lamellosa*, 10.75/0.25 m^2), and limpets (22.25/0.25 m^2) were the dominant fauna [Table 6-5]. Oil was not observed in the untreated quadrats along the upper elevation."
>
> "Oil in the form of mousse occurred on greywacke rock in the heavily treated area of the upper intertidal zone with the percent oil cover ranging from 5 to 35 percent [Table 6-5]. Live rockweed was very sparse (7-percent cover) and dead fronds were common in the upper intertidal zone in the heavily treated area. The biota was impoverished, but a small tide pool in one of the four upper intertidal quadrats in the treated area [see Figures F-3A, F-3B in Houghton et al. 1993] had more representative animals and algae than the remainder of that area. Overall in the treated area, cover of *N. larix*, *Odonthalia* [probably *Neorhodomela oregona*], and *C. dalli*, was lower than that in the untreated area. Numbers of limpets (0.75/0.25 m^2), and *N. lamellosa* (3.25/0.25 m^2) also were lower in the treated area while littorine snails were more abundant than in the untreated area."

The Category 3 middle station at the Northwest Bay West Arm rocky site showed only modest recovery by July 1991. Cover of *Fucus* and the opportunistic red *Gloiopeltis* expanded from 6.86 and 0 percent in 1989 to 36.8 and 7.2 percent, respectively, by 1991; the barnacles *S. balanoides* and *C. dalli* increased from 0.21 and 4.6 to 18.9 and 15.5 percent cover, respectively; *Littorina scutulata* increased from 9.9 to 312/0.25 m^2. No oil was seen in 1991.

Substantial additional recovery occurred at the Category 3 middle station between 1991 and 1992. The most evident change was the increase in post-sporeling rockweed cover from 34.4 percent in 1991 to 63 percent in 1992. Rockweed in the Category 3 site that had been noted as sporelings in 1990 photographs (see Figure F-3A in Houghton et al., 1993) had produced conceptacles and appeared to be reproductively mature. Cover of mature rockweed at the adjacent reference station had changed little over the four years (1989 through 1992). Cover of *Fucus* sporelings dropped at both stations from 1991 but was significantly greater at the reference station, where senescence of some plants allowed establishment of more sporelings.

Four species of red algae that represent a consistent understory of the undisturbed rocky community remained absent or virtually absent at the Category 3 station in 1992, and one other red (*Neorhodomela oregona*) was twice as abundant at the reference station. The opportunistic red alga *Gloiopeltis furcata*, which had been significantly more abundant at the Category 3 station in 1991, had dropped in cover by 1992 while increasing at the reference station, and the difference was no longer significant.

Table 6-5. Epibiota density/cover, Northwest Bay West Arm Middle Rocky Station, September 1989 (Houghton et al., 1990b).

	Reference (September 2, 1989)					Category 3 (September 2, 1989)					
Taxon	Mean	SD	Min	Max	Rep	Mean	SD	Min	Max	Rep	Percent difference
Plants (% cover)											
Encrusting coralline algae	1.38	1.56	0	4	4	0	0	0	0	4	-100.0
Encrusting noncoralline algae	9.50	8.20	1	20	4	15.19	12.60	0	35	4	59.9
Filamentous green algae	0.13	0.22	0	0.5	4	2.13	1.82	0	5	4	1538.5
Filamentous red algae	1.25	2.17	0	5	4	0	0	0	0	4	-100.0
Fucus gardneri	87.50	7.50	75	95	4	6.86	5.37	0	15	4	-92.2 **
Gigartinaceae	0.88	0.22	0.5	1	4	0.86	0.72	0	2	4	-2.3
Halosaccion glandiforme	0.38	0.22	0	0.5	4	0	0	0	0	4	-100.0
Neorhodomela larix	6.25	10.83	0	25	4	0	0	0	0	4	-100.0
Odonthalia sp.	8.25	5.54	1	15	4	6.34	5.49	0	15	4	-23.2
Ulva/Ulvaria spp.	0.13	0.22	0	0.5	4	0	0	0	0	4	-100.0
Total number plant taxa	10.00	-	-	-	4	6.00	-	-	-	4	-40.0
Total plant cover	115.63	-	-	-	4	31.59	-	-	-	4	-72.7
Animals (counts or % cover)											
Chthamalus dalli (%)	9.25	6.76	3	20	4	4.60	3.31	1	10	4	-50.3
Mytilus edulis (%)	0	0	0	0	4	0.21	0.18	0	0.5	4	a
Semibalanus balanoides (%)	0	0	0	0	4	0.21	0.18	0	0.5	4	a
Semibalanus cariosus (%)	0.50	0.35	0	1	4	0.25	0.18	0	0.5	4	-50.0
Actiniidae	0.25	0.43	0	1	4	0	0	0	0	4	-100.0
Cottidae	0	0	0	0	4	0.42	0.37	0	1	4	a
Littorina scutulata	0.25	0.43	0	1	4	9.89	6.40	2	19	4	3856.0 **
Littorina sitkana	1.75	1.79	0	4	4	2.20	1.80	0	5	4	25.7
Lottiidae	22.25	11.12	12	41	4	0.89	0.72	0	2	4	-96.0 **
Nucella lamellosa	10.75	14.08	1	35	4	2.89	1.41	1.299	5	4	-73.1
Pagurus hirsutiusculus	3.00	1.58	1	5	4	6.10	5.03	0	14	4	103.3
Siphonaria thersites	3.75	1.30	2	5	4	0	0	0	0	4	-100.0 **
Number animal taxa	9.00	-	-	-	4	9.00	-	-	-	4	0.0
Dead plants (% cover)											
Articulated coralline algae (dead)	0	0	0	0	4	0.21	0.18	0	0.5	4	a
Encrusting coralline algae (dead)	0.25	0.43	0	1	4	7.65	4.75	2	15	4	2960.0 **
Fucus gardneri (dead)	1.50	2.60	0	6	4	8.95	7.02	0.5	20	4	496.7
Dead animals (counts)											
Modiolus modiolus (dead)	0	0	0	0	4	0.42	0.37	0	1	4	a
Physical											
Bedrock (%)	100.00	0	100	100	4	69.66	36.64	7.395	100	4	-30.3
Cobble/gravel (%)	0	0	0	0	4	4.47	3.58	0	10	4	a
Oil cover (%)	0	0	0	0	4	18.35	11.49	5	35	4	a **
Oil scale (%)	0	0	0	0	4	1.50	0.87	0	2	4	a **
Tidepool (%)	0	0	0	0	4	8.42	7.36	0	20	4	a

a Indicates category not present at reference station.
** Indicates significance between heavily treated and lightly treated ($p < 0.05$) in 2-tailed t-test.

Total algal cover increased from 1991 to 1992 at the Category 3 station and decreased at the reference station but was still significantly greater at the reference station ($p = 0.008$). The difference in mean total number of algal taxa between the two stations increased in 1992, a trend contrary to the recovery and probably the result of increased *Fucus* dominance that excluded some other species on the Category 3 station. Thus, despite recovery in the rockweed population, the algal community at the Category 3 station remained significantly different from that at the reference station.

As with the plants, dominant animals showed signs of recovery between 1991 and 1992. Both mean number of individuals and mean number of taxa increased at the Category 3 station, but the difference in species richness (number of animal taxa) became more pronounced in 1992 ($p = 0.03$). The opportunistic barnacle *S. balanoides* remained significantly more abundant at the Category 3 station following the heavy colonization of the bare substratum that occurred in 1990-1991. Overall cover of this species at the Category 3 station declined somewhat between 1991 and 1992, perhaps because of predation by the increased numbers of the drill *Nucella lamellosa*. This drill, which had very low densities at the Category 3 station in 1991, was twice as abundant there as at the reference station in 1992; since this species lacks a planktonic larval stage, increased numbers probably resulted from feeding migrations from the adjacent reference area.

The littorine *L. sitkana*, another gastropod that lacks planktonic larvae for dispersal and that had been significantly less abundant at the Category 3 station in 1991, also had recolonized to the point where it was more abundant there than at the reference station. Its opportunistic congener *L. scutulata*, which has planktonic larvae, remained far more abundant at the Category 3 station. Two animals that were significantly less abundant at the Category 3 station in 1991 remained so in 1992, the hermit crab *Pagurus hirsutiusculus* and the pulmonate *Siphonaria thersites*.

The higher numbers of animals and lower numbers of animal taxa at the Category 3 station than in the reference area in both 1991 and 1992 indicate that normal biological controls have not yet become reestablished and that full recovery is probably several years away.

NORTH ELRINGTON ISLAND STUDIES

North Elrington Islet Upper Stations

Three Category 3 upper stations were sampled at Elrington Islet (north end of Elrington Island) for the first time in 1992 to assess the effects of different exposures on recovery patterns. It is presumed on the basis of 1989 records and observations that all three sides of the islet were hot-water washed in late summer of 1989. The Elrington Islet North site (most exposed to wave action) had the highest cover of *Fucus* at about 30 percent; the Elrington Islet West site had about 20 percent cover of *Fucus*, and the Elrington Islet East site had only about one percent cover of *Fucus* (Figure 6-1). The encrusting red alga *Hildenbrandia rubra* was found mainly at the West site (24.4 percent), though it was also found at a lower abundance at the other two sites (North 8.5 percent; East 1.1 percent; Table 6-6). This difference was significant in a randomized ANOVA ($p = 0.05$) and between West and East sites in a t-test ($p < 0.10$).

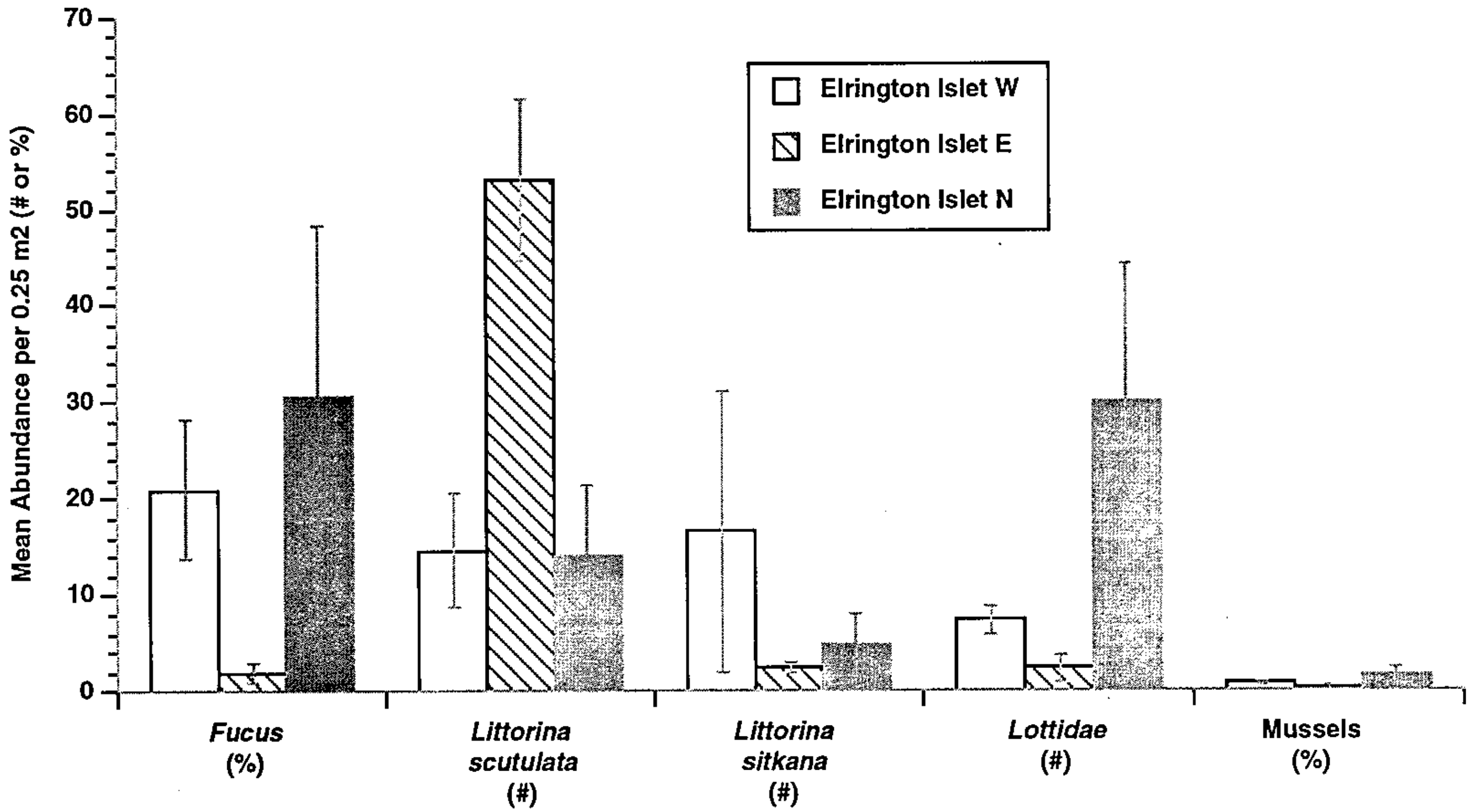

Figure 6-1. Upper Elrington Islet epibiota July 1992; mean abundance ± 1 SE.

Littorina scutulata numbers were significantly different among sites ($p < 0.10$ ANOVA); the East site had significantly higher numbers than the others in t-tests ($p < 0.10$ for both comparisons). *Littorina sitkana* abundance was highest at the West site, but this difference was not significant. Limpets were much higher in abundance at the North site, and mussels were found in about equal abundances at all three. The pulmonate gastropod *Siphonaria thersites* was found only at the North site (Table 6-6). Total plant cover, mainly from *Fucus* and *Hildenbrandia* (each more than 20 percent; Table 6-6), was highest at the West site, and there were means of 6.4 plant taxa and 1.2 animal taxa at this site. The North site had a total plant cover of 46.7 percent with means of 6.6 plant taxa and 9.4 animal taxa. The West station only had 3.0 percent total plant cover and means of 2.4 plant and 11 animal taxa. Continued monitoring of these sites in future years will be necessary to track convergence of the assemblages on each side of the islet as recovery progresses.

North Elrington Island Middle Stations

The middle rocky stations at Elrington East and Elrington West were compared to examine differences in areas known to have received different treatment methods (Houghton et al., 1990b). These transects were first sampled on September 4 and 5, 1989, prior to treatment, and again immediately after treatment on September 13 through 15, 1989. The Elrington West area was high-pressure hot-water washed with Omni-barges. The Elrington East area was cleaned by beach crews using firehoses because the cove was too small and shallow for Omni-barges. Comparisons were made of epibiota immediately before and after treatment on each transect and of epibiota between the two transects. Transects were resampled in July 1992.

In 1989 significantly higher numbers of filamentous browns, *Pilayella*, and *Pagurus hirsutiusculus* were found on the East transect following treatment ($p < 0.05$; t-test; Table 6-7). The increase in numbers of hermit crabs was probably due to aggregations of this scavenger on dead organisms following treatment, but higher abundances of the algal species immediately after treatment are explained only by differences in observer counts because the same quadrats were examined pre- and post-treatment. On the West transect significantly higher abundance of *Elachista fucicola* was found, while significantly lower abundance of *Fucus* was seen. Total plant cover was reduced following treatment on the West transect but not on the East transect (Figure 6-2).

In 1992 the Omni-barge-treated West site was found to have significantly lower abundances of *Fucus gardneri* and the hermit crab *Pagurus hirsutiusculus* (randomized t-test, $p < 0.01$) and flagelliform brown algae (t-test; $p < 0.05$; Table 6-7). Total plant cover was much lower at the West site, but more plant and animal taxa were found at the West site (Table 6-7). The firehose-treated East site had significantly lower numbers of the barnacles *Balanus glandula*, *Chthamalus dalli*, and *Semibalanus balanoides*, adult and juvenile limpets, and mussel spat ($p < 0.01$). Increases in abundance from 1989 to 1992 have been most dramatic for *Fucus* and *Pagurus* on the East transect and for limpets, *Chthamalus*, and *S. balanoides* on the West transect (Figure 6-2).

Table 6-6. Rocky upper intertidal epibiota from three transects at Elrington Islet, July 1992 ($*p < 0.10$; $**p < 0.05$).

	Elrington Islet E		Elrington Islet N		Elrington Islet W		ANOVA	t-test		
Taxon	Mean	SD	Mean	SD	Mean	SD		E vs N	E vs W	N vs W
Plants (% cover)										
Blue-green algae, crust	0.00	0.00	2.90	2.46	0.00	0.00	**	*		*
Endozoic green algae	0.00	0.00	0.90	1.19	0.40	0.22		*	*	
Fucus gardneri	1.40	2.19	30.00	39.17	20.50	15.98			*	
Fucus gardneri (sporelings)	0.50	0.00	0.60	0.42	0.50	0.35				
Gloiopeltis furcata	0.00	0.00	1.50	3.08	0.30	0.45				
Hildenbrandia rubra	1.10	0.55	8.50	12.68	24.40	13.01	*		*	
Verrucaria spp.	0.00	0.00	1.30	1.20	0.90	0.65		*	**	
Black crust (maybe Hildenbrandia)	0.00	0.00	0.10	0.22	2.50	2.40	**		*	
Total plant cover (%)	**3.00**		**46.70**		**49.80**					
Number of plant taxa ◊	**2.40**		**6.60**		**6.40**					
Animals (% cover or no./0.25 square m)										
Balanus glandula (%)	2.20	2.77	13.20	11.34	0.70	1.30	**			**
Balanus glandula (% set)	0.50	0.35	0.00	0.00	0.00	0.00	**	*	*	
Chthamalus dalli (% set)	1.20	0.84	0.90	1.19	0.00	0.00			*	*
Chthamalus dalli (%)	0.10	0.22	5.30	5.83	0.40	0.22		*		
Mytilus edulis (%)	0.00	0.00	0.80	0.84	0.80	0.27			**	
Semibalanus balanoides (%)	1.30	2.08	3.20	6.61	0.60	0.22				
Littorina scutulata (#)	53.00	18.85	14.00	16.32	14.60	13.24	*		*	
Littorina sitkana (#)	2.40	1.14	4.80	6.91	16.60	32.78				
Lottia pelta (#)	0.60	1.34	10.80	12.83	4.00	3.87				
Lottia strigatella (#)	1.20	1.64	7.60	13.74	3.00	2.55				
Lottiidae, unid. (#)	0.00	0.00	10.40	14.31	0.00	0.00				
Siphonaria thersites (#)	0.00	0.00	7.20	11.99	0.00	0.00	*			
Ligia sp. (#)	0.60	0.89	2.00	2.35	0.00	0.00				
Number of animal taxa ◊	**6.80**	**2.95**	**9.40**	**2.70**	**7.20**	**1.48**				
Other (% cover or #)										
Oil scale (#) (primary)	0.00	0.00	1.20	2.68	2.40	3.29				
Oil cover (%) (primary)	0.00	0.00	0.10	0.22	0.30	0.45				
Rock (%)	100.00	0.00	100.00	0.00	100.00	0.00				
Water (%)	0.00	0.00	0.00	0.00	1.70	2.22	*			

◊ See detailed species list in Appendix C for the total number of taxa.

Table 6-7. Mean abundance (% or no./0.25 square m) of important epibiota at Elrington Island East and West middle rocky intertidal sites, 1989 and 1992 (* = $p < 0.05$; ** = $p < 0.01$).

	Elrington East						Elrington West						1989	1989	1992
	Pre-treatment		Post-treatment		1992		Pre-treatment		Post-treatment		1992		Pre- vs. post-	Pre- vs. post-	E vs. W
Lumped taxon	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	t-test E	t-test W	t-test
Plants (% cover)															
Elachista fucicola	3.20	1.89	4.40	5.89	2.00	2.67	0.00		0.20	0.24	1.05	1.61		*	
Encrusting non coralline algae	46.60	21.66	52.35	30.15	29.00	26.93	45.65	32.18	34.90	27.46	12.75	16.36			
Filamentous Chlorophyta	10.75	15.72	11.95	25.00	2.90	7.77	1.65	2.90	1.05	1.59	0.65	1.03			
Filamentous Phaeophyta	2.05	3.03	2.25	5.93	8.90	7.08	0.00		0.05	0.15	3.25	6.19	*		
Flagelliform Phaeophyta	0.35	0.32	0.15	0.23	1.30	1.44	0.00		0.05	0.15	0.15	0.24	*		*
Fucus gardneri	28.00	19.77	24.90	23.69	67.00	24.86	32.05	19.18	18.00	8.46	26.50	28.66		*	**
Gigartinaceae	1.15	1.07	0.85	0.63	1.25	1.16	1.35	1.91	2.15	3.64	0.80	1.46			
Pilayella spp.	0.55	0.57	2.60	3.52	0.00		4.50	8.60	2.75	3.22	0.00		*		
Rhodomelaceae/Cryptosiphonia sp.	0.10	0.20	0.05		0.15	0.34	0.45	0.35	0.40		1.80	2.78			
Total plant cover	**94.05**		**100.00**		**143.45**		**86.35**		**60.65**		**62.85**				
Number of plant taxa ◊	**15**		**11**		**20**		**12**		**16**		**22**				
Animals (% cover or no./0.25 square m)															
Balanus glandula (%)	0.00		0.00		0.00		0.00		1.05	2.67	1.20	1.65			**
Chthamalus dalli (%)	0.25	0.25	0.15	0.23	0.30	0.35	0.25	0.25	0.25	0.25	2.05	2.24			**
Littorina scutulata (#)	0.00		0.30	0.90	0.80	2.20	4.00	6.43	2.40	3.93	2.70	5.93			
Littorina sitkana (#)	0.00		0.10	0.30	0.30	0.95	6.20	12.53	2.00	2.68	0.50	0.97			
Lottiidae (#)	0.80	1.54	1.20	1.33	4.90	3.38	9.90	11.67	4.00	5.90	30.40	44.31			**
Lottiidae (juv.) (#)	0.00		0.00		0.20	0.42	0.00		0.00		14.30	19.60			**
Mytilus edulis (%)	0.00		0.00		0.05	0.16	0.15	0.23	0.15	0.23	0.85	1.58			
Pagurus hirsutiusculus (#)	3.90	4.09	9.20	10.05	42.40	36.47	0.40	0.92	0.20	0.40	4.30	6.24	*		**
Semibalanus balanoides (%)	0.15	0.23	0.00		0.10	0.21	2.50	3.38	2.00	4.34	7.40	9.72			**
Number of animal taxa ◊	**12**		**13**		**16**		**9**		**11**		**19**				
Other (% cover)															
Boulder/cobble	61.90		70.6		61.60	44.63	100.00		88.30		94.70	12.60	*		
Gravel/sand	3.10	4.61	0.2	0.6	2.15	2.77	0.00		0.00		1.30	3.20			
Oil cover (primary) (%)	3.20	5.71	14.4	23.85	0.00		1.90	2.17	32.20	23.31	0.10	0.32		*	
Oil scale (primary) (#)	0.70	0.46	1.2	0.6	0.00		1.80	2.09	1.95	0.82	0.60	1.90			
Rock	35.00	38.99	28.5	35.71	36.30	45.52	0.00		11.70	29.87	4.00	12.65	*		

◊ See detailed species list in Appendix C for the total number of taxa.

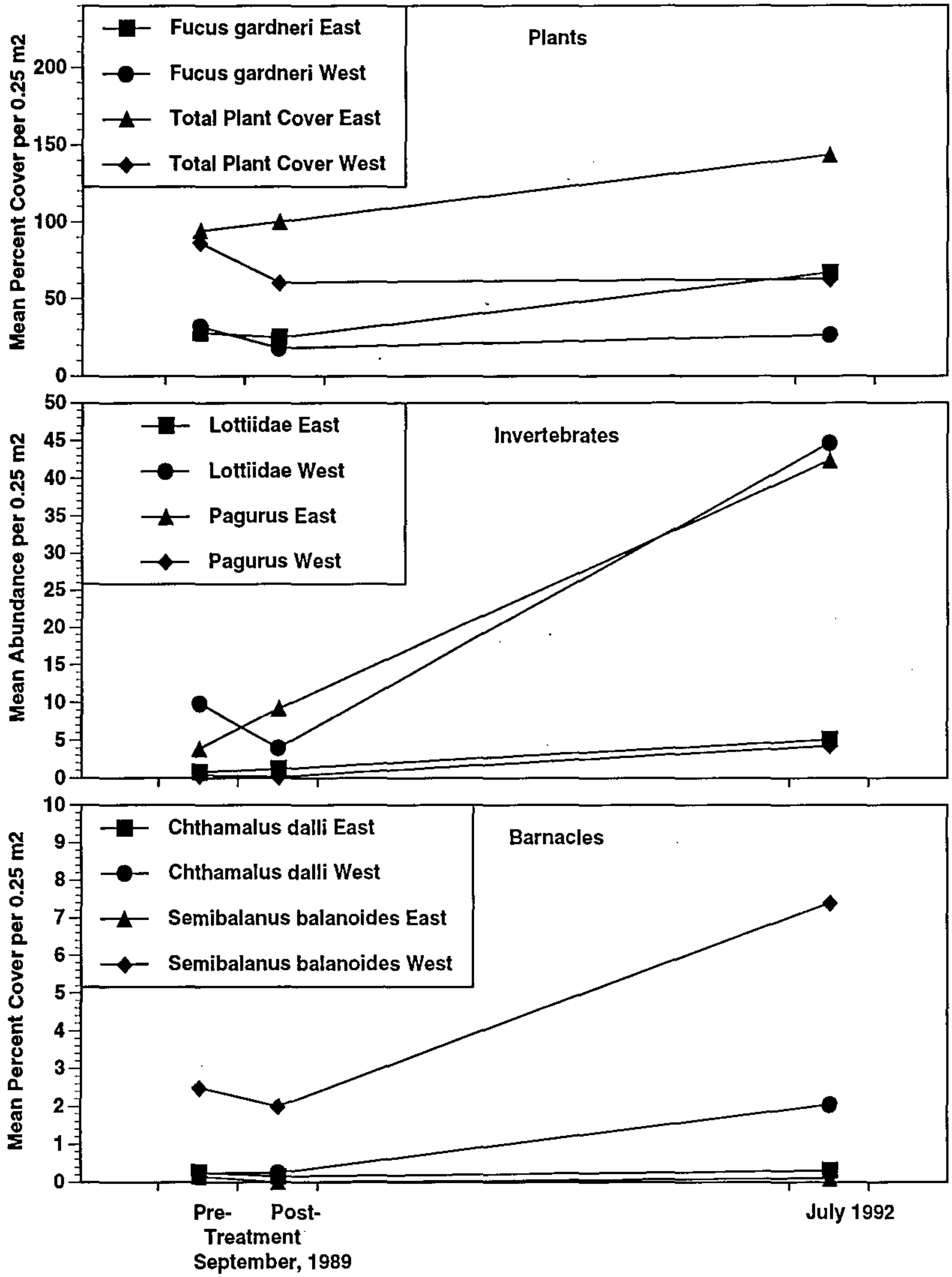

Figure 6-2. Mean abundance of select plant and animal taxa from North Elrington Island East and West transects, 1989 and 1992.

Sampling of the two North Elrington Island sites has provided an insight into differences in intertidal assemblages that possibly resulted from different treatment methods. The more intensively treated West site had significantly lower abundances of *Fucus* cover and higher abundances of three barnacle species. Both transects were at about the same tidal elevation and had the same exposure, so physical factors probably have not factored in recovery of these species. Sampling of the sites prior to treatment (Houghton et al., 1990b) revealed that the dominant algal taxa in both transects were *Fucus* and encrusting noncoralline algae; total plant cover was about the same in both transects (Table 6-7). Immediately after treatment, mean cover of *Fucus* on the East transect was reduced by 1.8 percent to 24.9 percent cover—not a significant difference. In contrast, on the West transect mean cover of *Fucus* was reduced by 36 percent to 18 percent cover, a significantly lower difference ($p < 0.05$). In 1992 *Fucus* cover was significantly higher on the East transect than on the West transect ($p < 0.01$; Table 6-7). The decrease in encrusting algae along with low numbers of grazers such as littorines and limpets on the East transect may account for this rapid increase of *Fucus*. In addition, the use of less intensive cleanup methods in this area resulted in a smaller loss of *Fucus* that probably also contributed to the increase of *Fucus* over the past three years. The more intensively treated West transect had a significant drop in *Fucus* cover immediately after treatment and has yet to recover to pretreatment levels. Significantly higher numbers of limpets along this transect may be an important factor in the low total plant cover and in relatively low *Fucus* cover here.

HERRING BAY OMNI-BARGE TEST SITE

One of the definitive tests demonstrating the adverse short-term effects of high-pressure hot-water washes on epibiota in Prince William Sound was the July 1989 Omni-barge test conducted at the north side of the entrance to Herring Bay (Figure 1-1). This study clearly showed the major and significant impacts of washing of two durations (95 minutes and 165 minutes) on epibiota that had survived about four months on a heavily oiled boulder beach (Houghton et al., 1990a, 1991a; Lees et al., 1993). In 1992 this site was revisited and the middle elevation resampled to evaluate recovery.

Methods

On June 28, 1992, the transects sampled in 1989 in the upper portion of the *Fucus* zone (about 5.5 feet MLLW) were relocated on the basis of photographs and stakes marking some quadrats and sampled. Because the areas subjected to the two treatment durations were small and contiguous and had similar impacts on epibiota, the entire area of the moderate and extended washes was resampled as a single middle elevation station in 1992. Locations with stakes remaining were sampled along with additional, randomly selected locations for a total of ten quadrats.

Results

The general appearance of the Omni-barge test site in 1992 was of a *Fucus*- dominated boulder beach with no obvious sign of oiling. Epibiota data from 1992 (Table 6-8) confirm that much movement has been made toward recovery, although the condition of the epibiota in relation to its prespill condition cannot be determined because there are no data from comparable unoiled (control) sites.

Table 6-8. Comparison of important intertidal epibiota from Omni site, 1989 and 1992.

	July 1989					
	Pre-treatment		Post-treatment		July 1992	
	Mean	SD	Mean	SD	Mean	SD
Plants (% cover)						
Blue-green algae, crust					1.10	2.08
Endocladia/Gloiopeltis	0.35		0.05			
Endozoic green algae					0.05	0.16
Filamentous green algae	0.30		0.05			
Fucus gardneri	25.80		2.50		68.00	17.67
Fucus gardneri, sporelings					0.20	0.26
Gloiopeltis furcata					1.90	1.88
Hildenbrandia rubra					8.00	8.82
Pilayella littoralis	0.05		0.05			
Ralfsia spp.					1.45	2.24
Animals (% cover or no./0.25 square m)						
Asterozoa, unid. (#)	0.10		0.00			
Balanus crenatus? (%)	0.30		0.75			
Balanus glandula (%)					0.10	0.21
Balanus rostratus (%)						
Balanus/Semibalanus spp.(% set)	0.05		0.00		0.00	0.00
Chthamalus dalli (%)					0.45	0.28
Clinocottus acuticeps (#)	0.00		0.10		0.00	0.00
Encrusting bryozoan (%)					0.20	0.63
Gnorimosphaeroma oregonensis (#)					0.50	1.58
Hiatella arctica (#)					0.10	0.32
Lacuna vincta (#)	0.30		0.00			
Littorina scutulata (juv.) (#)					58.20	81.39
Littorina scutulata (#)	48.40		0.00		34.40	44.27
Littorina sitkana (#)	16.50		0.00		358.00	165.55
Lotiidae, unid.(#)	11.30		0.00		8.50	3.46
Mytilis edulis, spat (%)					0.40	0.61
Mytilis edulis (%)	3.70		1.75		1.00	0.88
Nucella lima (#)	0.30		0.00		0.90	2.51
Pagurus beringanus (#)					0.90	1.52
Pagurus hirsutiusculus (#)	0.10		0.40		18.90	45.77
Pentidotea wosnesenskii (#)					1.10	1.60
Semibalanus balanoides, set (%)					23.00	11.78
Semibalanus balanoides (%)	8.65		8.35		1.05	0.55
Semibalanus cariosus (%)	0.00		0.50		0.00	0.00
Plants (dead) (% cover)						
Fucus gardneri	0.00		17.30			
Animals (dead) (% cover or no./.25 square m)						
Balanus/Semibalanus spp. (%)	2.15		2.50		0.15	0.34
Mytilus edulis (#)	5.40		32.90		0.10	0.32
Nucella lima (moribund) (#)	0.00		0.30			
Semibalanus balanoides (%)					0.10	0.21
Volutharpa ampullacea (#)	0.00		0.10			
Oiling						
Oil cover, primary (%)	73.30		67.50		0.00	0.00
Oil scale, primary (#)	5.00		2.60		0.00	0.00

As could be expected because of the relatively exposed orientation of the site, oil in the form of heavy sheens and mousse that covered 67.5 percent of the substratum after washing in 1989 was absent in 1992. *Fucus*, which in July 1989 had 25.8 percent cover that was largely eliminated by treatment, had expanded to 68 percent cover in July 1992 (Table 6-8). This response is similar to that seen on rocky Category 3 middle stations and is likely in response to an extended period of reduced grazer populations. Encrusting red and blue-green algae as well as the opportunistic red *Gloiopeltis* were much more abundant in 1992 than in 1989.

Of the animals that were severely impacted by treatment, most had recovered by 1992. *Littorina scutulata* and especially *L. sitkana*, both of which were eliminated by treatment, had recovered to well above pretreatment levels. Limpets also had nearly recovered to pretreatment levels, although abundances were probably below prespill levels. Mussels were somewhat less abundant in 1992 than they were prior to treatment, but the drill *Nucella lima* and hermit crabs (two species) were far more abundant than before treatment. Finally, the barnacle *Semibalanus balanoides*, which appeared to have survived treatment without significant impact (8.35 percent post-treatment cover; Table 6-8), had declined by 1992 to only 1.05 percent cover. Recolonization was evident, however, from 23 percent cover of new *S. balanoides* set.

Discussion

The Omni-barge site seems to have largely recovered from the treatments administered in 1989. Whether the course of recovery was accelerated, slowed, or altered by the treatments cannot be determined because of the lack of reference stations. Based on the results of the 1990 to 1992 epibiota studies (Chapter 3), it appears that recovery would have been faster without the high-pressure hot-water washes; rockweed cover, mussel cover, and other normally dominant species such as littorines, limpets, and drills would have remained to provide biological habitat and biological controls necessary for maintenance of the undisturbed assemblage. Removal of all of these components of the assemblage required that they become reestablished through colonization or immigration. This condition has been widely reported in oil spills (e.g., Southward and Southward, 1978) and removal experiments (e.g., Dayton, 1971) to result in wide fluctuations in abundance of species until the normal biological controls of grazing and predation become established.

POINT HELEN MIDDLE BOULDER/COBBLE

A middle elevation boulder/cobble station was added at Point Helen (designated as Point Helen S) in 1992. This station is south of the previously sampled site at Point Helen (Point Helen N3). Extensive berm relocation activities occurred here in August 1991 (J. Michel, personal communication), and concerns were expressed about the effects of movements of the substrata on biota in the area. Substrata at both sites were essentially the same; each station had 93 to 95 percent boulder/ cobble. No plant species were found at Point Helen S (Appendix Table C-2-2). Only two plant taxa, comprising a total of 0.25 percent cover, were found at the Point Helen N3 station. All animal taxa except for the barnacle *Semibalanus balanoides* and the pulmonate snail *Siphonaria thersites* were found in higher abundance at the N3 station. There were significantly higher numbers of littorines of both species (randomization t-test; $p < 0.05$) along with significantly higher numbers of juvenile limpets ($p < 0.10$) at the N3 site.

Slight decreases in abundance of some taxa including *Fucus, Balanus glandula, Semibalanus balanoides, Chthamalus dalli,* and *Mytilus* were seen at the Point Helen S site following treatment in September 1989 (Table 6-9). These 1989 data indicate little impact of treatment at this site. In July 1992, following the 1991 storm berm relocation (Michel and Hayes, 1993), only minimal additional change was evident from September 1989 (Table 6-9). *Littorina scutulata* decreased from 20 to 26/0.25 m^2 in 1989 to 13/0.25 m^2 in 1992, but *L. sitkana* increased from 2 to 5/0.25 m^2 to more than 26/0.25 m^2. Lack of substantial biota at this station may be in part the result of the berm relocation. For the berm relocation, gravel, cobbles, and small boulders were displaced into the middle intertidal (Michel and Hayes, 1993), where the movement of these rocks during strong surges and storms probably crushed many of the animals. The boulder/cobble habitat and high exposure at Point Helen naturally results in low abundances of biota, but the increased instability of the substrata probably has precluded settlement and survival of many organisms. This argument is supported by comparison of the Point Helen S site to the Point Helen N3 site. These two sites have the same exposure and are located about one-quarter mile apart. The Point Helen N3 site had significantly higher numbers of littorines and limpets (t-tests; Table 6-9) and some algal cover compared to no algal cover at all at the Point Helen S site.

SMITH ISLAND MUSSEL TRANSPLANT STUDY

Background

Smith Island, in north-central Prince William Sound (Figure 1-1), was heavily impacted by the Alaska North Slope Bay crude oil spilled from the tanker *Exxon Valdez*. Located approximately 25 miles from the grounding site at Bligh Reef, Smith Island—and in particular, its northern shore—was directly in the path of the oil slick as it moved to the southwest. On March 26, 1989, Smith Island was very heavily oiled by relatively fresh crude oil when winds in excess of 70 knots initially blew the slick ashore (Michel and Hayes, 1991). The large grain size that characterized many of the beaches on the island permitted the crude oil to penetrate deeply, where it proved persistent and difficult to remove.

In 1989 and 1990 many of the heavily oiled beaches along the northern shoreline of Smith Island were aggressively cleaned, with high-pressure hot-water, chemical cleaners, mechanical tilling and movement of portions of the beaches with heavy equipment, and bioremediation (see Appendix A-1 in Houghton et al., 1993). All of these remedial efforts required large numbers of personnel and logistical support. Despite the scale of these efforts, subsurface pockets of oil remained afterward at some beaches on the north side of the island, including the site sampled for this study.

Table 6-9. Mean abundance (% or no./0.25 square m) of important epibiota at two Point Helen middle boulder/cobble sites, July 1992, and from pre- and post-treatment sampling at Point Helen S, September 1989 (* = $p < 0.10$; ** = $p < 0.05$; *** = $p < 0.01$).

Taxa	Pt. Helen S Pre- Mean	Pt. Helen S Pre- SD	Pt. Helen S Post- Mean	Pt. Helen S Post- SD	Pt. Helen S 1992 Mean	Pt. Helen S 1992 SD	Pt. Helen N3 1992 Mean	Pt. Helen N3 1992 SD	t-test 1992 S vs. N3
Plants (% cover)									
Endocladiaceae	0.00	0.00	0.00	0.00	0.00	0.00	0.15	0.24	
Fucus gardneri	0.25	0.63	0.10	0.21	0.00	0.00	0.10	0.21	
Total plant cover (%)	**0.25**		**0.15**		**0.00**		**0.25**		
Number of plant taxa ◊	**1**		**2**		**0**		**2**		
Animals (% cover or no./0.25 square m)									
Balanus glandula (%)	0.45	0.64	0.35	0.34	0.20	0.27	0.20	0.26	
Balanus/Semibalanus spp (%)	0.25	0.24	0.00	0.00	0.00	0.00	0.35	0.24	
Chthamalus dalli (%)	0.25	0.26	0.15	0.24	0.50	0.00	0.55	0.37	
Littorina scutulata (#)	20.00	38.18	26.20	30.36	13.00	16.45	32.70	36.21	**
Littorina sitkana (#)	2.56	4.98	4.90	5.32	25.60	31.00	105.60	106.44	**
Littorina spp. (juv) (#)	0.00	0.00	0.00	0.00	0.00	0.00	101.10	212.13	***
Lottiidae (#)	0.80	1.40	1.50	2.51	5.60	6.35	7.30	8.00	
Lottiidae (juv.) (#)	0.00	0.00	0.00	0.00	8.40	18.78	28.30	35.40	*
Mytilus edulis (%)	0.30	0.42	0.20	0.26	0.00	0.00	0.35	0.24	
Mytilidae, (spat) (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.35	0.24	
Pisces (#)	0.00	0.00	0.00	0.00	0.20	0.45	0.00	0.00	
Semibalanus balanoides (%)	1.00	1.62	0.20	0.35	0.50	0.00	0.20	0.26	
Siphonaria thersites (#)	0.00	0.00	0.00	0.00	1.60	3.58	0.00	0.00	
Number of animal taxa ◊	**9**		**7**		**7**		**8**		
Dead organisms (% cover or no./0.25 square m)									
Balanus glandula (dead) (%)	0.40	0.70	0.25	0.26	0.30	0.27	0.15	0.24	
Chthamalus dalli (dead) (%)	0.05	0.16	0.40	0.21	0.30	0.27	0.10	0.21	
Mytilus edulis (dead) (#)	3.60	8.28	1.50	4.09	0.00	0.00	0.20	0.42	
Semibalanus balanoides (dead) (%)	0.15	0.34	0.20	0.35	0.30	0.27	0.20	0.26	
Spirorbidae (dead) (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.16	

Table 6.9 (continued)

Taxa	Pt. Helen S Pre- Mean	SD	Pt. Helen S Post- Mean	SD	Pt. Helen S 1992 Mean	SD	Pt. Helen N3 1992 Mean	SD	t-test 1992 S vs. N3
Other (% cover or #)									
Boulder/cobble (%)	100.00	0.00	100.00	0.00	93.00	15.65	95.40	5.82	
Gravel/sand (%)	0.00	0.00	0.00	0.00	0.00	0.00	4.60	5.82	
Oil cover (primary) (%)	61.00	31.69	39.00	29.21	0.10	0.22	0.05	0.16	
Oil scale (primary) (#)	2.50	0.53	4.60	0.52	1.20	2.68	0.60	1.90	
Rock (%)	0.00	0.00	0.00	0.00	7.00	15.65	0.00	0.00	
Water (%)	0.00	0.00	0.00	0.00	4.00	8.94	0.00	0.00	

◊ See detailed species list in Appendix C for the total number of taxa.

In 1990 Smith Island was visited for the first time for the biological monitoring study (Houghton et al. 1991a)[1]. As detailed previously (Chapter 2), an integral part of the monitoring effort has been the collection of mussel (*Mytilus* cf. *trossulus*) tissue samples, which were subsequently analyzed by GC/MS for levels of PAHs. Bivalve mollusks of this genus have been extensively used as "sentinel" or biomonitoring organisms in many programs around the world (Goldberg et al., 1978; Widdows and Donkin, 1992), and results for levels of hydrocarbons in mussels in Prince William Sound have been used as an indicator of biological availability of residual PAHs.

In the 1990 collections and analyses, mussels from the Smith Island site contained the highest levels of total target PAHs, 84,000 ppb dry weight, of the 23 sites sampled for the monitoring program. In contrast, 21 of the 23 mussel samples had PAH levels of 8,000 ppb or less (Houghton et al., 1991a).

In order to investigate the elevated concentrations found in mussels at the Smith Island site, in 1991 a transplant experiment was implemented in which mussels from a reference site in Prince William Sound (Eshamy Bay) were moved to Smith Island. The results of this experiment are summarized in Houghton et al. (1993). The mussels were deployed for a two-month period, after which they were collected and analyzed by GC/MS for tissue PAH levels. Transplanted mussels showed a significant uptake of PAHs over the two-month period: the Eshamy Bay transplant stock contained 760 ppb, and samples of this stock transplanted to the east and west ends of the beach site on the north side of Smith Island contained 20,000 and 4,800 ppb, respectively, upon collection two months later.

In 1992, the mussel transplant experiment at Smith Island was expanded to further investigate and define conditions there. This included an increased level of mussel transplant effort, as well as the incorporation of a new monitoring tool, the SPMD, into the study. SPMDs are a recently developed tool for assessing availability of nonpolar organic compounds to aquatic organisms and for estimating concentrations of such materials in the environment (Huckins et al., 1990). Developed by research chemists at the U. S. Fish and Wildlife Service, National Fisheries Contaminant Research Center in Columbia, Missouri, SPMDs are simple in design; each consists of a heat-sealed low-density polyethylene bag containing triolein lipid. Transient holes in the polyethylene ranging from 5 to 10 Å in diameter are believed to permit dissolved low molecular weight lipophilic compounds to diffuse into the enclosed triolein, where they are retained until the SPMDs are recovered, extracted, and analyzed. The devices potentially offer several advantages over traditional biological monitoring tools such as bivalves, primarily consistency, comparability, and utility in highly contaminated situations where living sentinel organisms are not practical. In addition to assessing the extent to which PAHs were biologically available to intertidal organisms, one of the other objectives of this study was to evaluate the performance of SPMDs vis à vis mussels as oil spill monitoring tools.

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1 NOAA geomorphologists began documenting conditions on the island in 1989; see Michel and Hayes (1991).

Methods

Field Methods

Mussel collections

Mussels (*Mytilus* cf. *trossulus*) used as transplant stock for the experiment were collected on June 24, 1992, in Barnes Cove, Drier Bay, on the west side of Knight Island in the central part of Prince William Sound. Shoreline surveys conducted by state and federal agencies and Exxon indicated that this area had been only lightly impacted by oil from the spill, and GC/MS analyses of mussels collected at this site by chemists from the National Marine Fisheries Service laboratory at Auke Bay, Alaska, confirmed a low level of hydrocarbon contamination (Babcock et al., 1993). Collection was restricted to mussels with shells greater than 30 mm long to minimize variability due to size and age.

Three samples of the Barnes Cove mussels were collected for GC/MS analysis to quantify "baseline" levels of PAH contamination in the transplant stock. Each of these samples was composed of 25 individual mussels.

Semipermeable membrane devices

SPMDs for this study were prepared by the Battelle Marine Sciences Laboratory in Sequim, Washington, using the methods of Huckins et al. (1990).

Two SPMDs were prepared in the same batch as those deployed in the field but were held in sealed containers in the laboratory. These were considered method blanks and were analyzed by GC/MS when the field devices were returned to the laboratory.

Field design

Two 60-m study transects were established on Smith Island for the 1992 study. The first was located on June 25, 1992, at a previously established NOAA study site on the northwest side of the island, which had been heavily oiled (Figure 6-3). This transect was located in the middle intertidal zone, between two recognizable beach features (bedrock outcrops), and at an elevation where resident mussels were observed to occur. Survey instruments were used to determine the tidal elevation of the transect as ranging between +2.23 and +2.32 m MLLW.

Five stations were located on the north transect. The first station was randomly located at the 3-m mark, and the remaining four were located at equally spaced intervals of 14.25-m (17.25-, 31.50-, 45.75-, and 60-m marks on the transect). Each station was permanently marked with a 61-cm iron stake flagged with colored plastic survey tape and hammered into the beach.

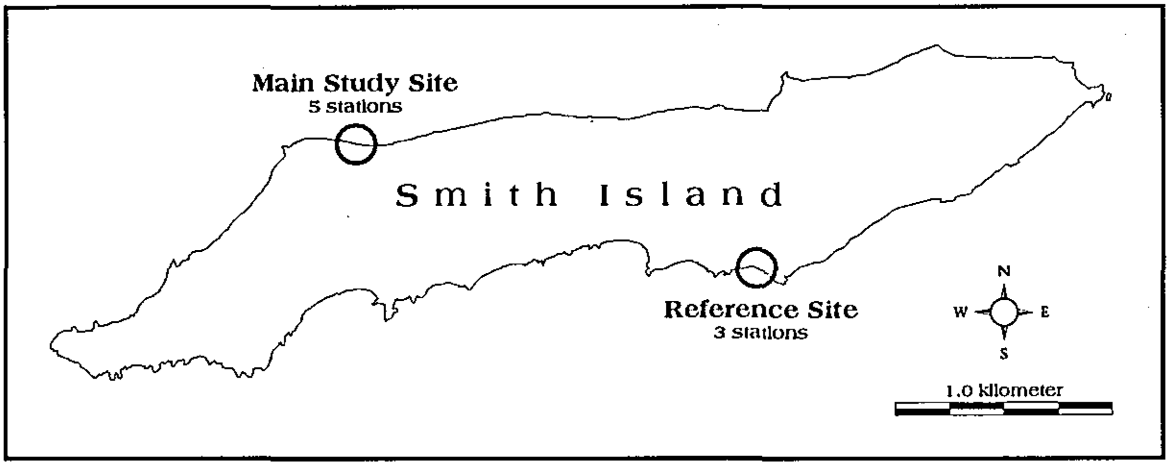

Figure 6-3. Location of study sites on Smith Island.

The second transect was established at a boulder/cobble beach on the southeast side of the island on June 25, 1992 (Figure 6-3). Shoreline assessment and cleanup records had indicated that beaches on this side of Smith Island had been oiled to a much lesser degree than had the northern beaches. To minimize differences attributable to beach elevations and submergence time, survey instruments were used to approximate the tidal elevation of the north transect. The range was +2.23 to +2.28 m MLLW. Three stations were located on the south transect. The first was randomly established at 8 m, and the other two were at equally spaced 26 m intervals (34- and 60-m marks on the transect).

At each station on both transects, the large boulders and cobbles overlying, or "armoring," smaller grained substratum underneath were removed. Once the armoring layer had been moved, samples of the gravel layer were collected in precleaned 500-ml jars for subsequent chemical analysis.

Three 10-by-10-by-15-cm vinyl-coated-wire cages were placed on the gravel substratum. Two of the cages contained a single SPMD each, and one contained 55 mussels collected from Barnes Cove. After the cages containing the SPMDs and mussels were placed on the gravel, cobbles, and boulders were placed around and on the cages to hold them in place.

The sites on the north and south sides of Smith Island were revisited on July 9, 1992, after a 14-day exposure. At each of the stations, one of the SPMDs and approximately 25 mussels were recovered. Following this collection, boulders and cobbles were replaced around and on the remaining cages. Final sample collection took place on August 16, 1992, or 52 days after deployment.

Chemical methods

Sediments and mussels

Chemical analyses were performed at two analytical facilities. Sediment and mussel tissue samples were sent to IES; analytical methods for sediment and mussel samples are detailed in Chapter 2. SPMDs were analyzed at Battelle Marine Sciences Laboratory in Sequim, Washington.

Results for a total of 37 PAHs were reported for sediments and mussels (Table 6-10). In SPMDs 36 PAHs were considered target compounds. There were 30 PAHs common to sediments/mussels and SPMDs. In the results and discussion to follow, the full array of PAH compounds is used when appropriate; when comparisons are made between SPMDs and one of the other matrices, only the 30 in-common compounds are considered.

Semipermeable membrane devices

Analytical methods for SPMDs were adapted from the procedures of Krahn et al. (1988a, b) and are essentially standard analytical methods used in the NOAA/National Status and Trends Program (Battelle Memorial Institute, 1990). Individual SPMDs were cleaned of algae and sediment with laboratory tissues and were then solvent-extracted for 24 hours in 100 ml of hexane containing stable isotopically labeled surrogate compounds and 10 grams (g) of anhydrous sodium sulfate. The extract was evaporated to a volume of 1.0 ml, processed by high performance liquid chromatography to remove possible interfering compounds, and then analyzed by GC/MS.

RESULTS

At the 14-day (July 9, 1993) collection, it was found that two of the SPMDs were no longer present in their cages. Wave and tidal activity had apparently removed the SPMDs through narrow spaces at the opening of the cages. These openings were secured during the July recovery. At that time, at those stations where an SPMD was missing, the remaining SPMD was collected, leaving none for collection at the subsequent visit. As a result of this strategy, however, a full set of eight SPMDs (five on the north side, three on the south side) was collected in July. A complete set of mussels was also sampled. Table 6-11 summarizes disposition of samples.

Table 6-10. List of target PAHs in sediments, mussels, and SPMDs.

PAH	Sediment	Mussel	SPMD
Naphthalene	✓	✓	✓
C-1 Naphthalene	✓	✓	✓
C-2 Naphthalene	✓	✓	✓
C-3 Naphthalene	✓	✓	✓
C-4 Naphthalene	✓	✓	✓
Acenaphthalene			✓
Acenaphthene			✓
Fluorene	✓	✓	✓
C-1 Fluorene	✓	✓	✓
C-2 Fluorene	✓	✓	✓
C-3 Fluorene	✓	✓	✓
Dibenzothiophene	✓	✓	✓
C-1 Dibenzothiophene	✓	✓	✓
C-2 Dibenzothiophene	✓	✓	✓
C-3 Dibenzothiophene	✓	✓	✓
Phenanthrene	✓	✓	✓
Anthracene	✓	✓	✓
C-1 Phenanthrene/Anthracene	✓	✓	✓
C-2 Phenanthrene/Anthracene	✓	✓	✓
C-3 Phenanthrene/Anthracene	✓	✓	✓
C-4 Phenanthrene/Anthracene			✓
Naphthobenzothiophene	✓	✓	
C-1 Naphthobenzothiophene	✓	✓	
C-2 Naphthobenzothiophene	✓	✓	
C-3 Naphthobenzothiophene	✓	✓	
Fluoranthene	✓	✓	✓
Pyrene	✓	✓	✓
C-1 Fluoranthene/Pyrene	✓	✓	✓
C-2 Pyrene	✓	✓	
Benzo(a)Anthracene	✓	✓	✓
Chrysene	✓	✓	✓
C-1 Chrysene	✓	✓	✓
C-2 Chrysene	✓	✓	✓
C-3 Chrysene			✓
C-4 Chrysene			✓
Benzo(b)Fluoranthene	✓	✓	✓
Benzo(k)Fluoranthene			✓
Benzo(e)Pyrene	✓	✓	
Benzo(a)Pyrene	✓	✓	✓
Perylene	✓	✓	
Indeno(1,2,3,-c,d)Pyrene	✓	✓	✓
Dibenzo(a,h)Anthracene	✓	✓	✓
Benzo(g,h,i)Perylene	✓	✓	✓

The sites were sampled for the final time on August 16, 1992, 52 days after deployment of the SPMDs and mussels. During this visit, it was apparent that one or more storm events had affected both sides of the island, as some of the stations had been disrupted and some cages were either missing or had been displaced on the beaches (Table 6-11).

Table 6-11. Disposition of samples deployed at Smith Island.

Sample-date	Station							
	N-1	N-2	N-3	N-4	N-5	S-1	S-2	S-3
Mussel-July	✓	✓	✓	✓	✓	✓	✓	✓
Mussel-August	*	✓	*	✓	✓	*	°	°
SPMD-July	✓	°	✓	✓	✓		✓	°
SPMD-August	*	X	°	°	✓	*	°	X

Key

✓ = Sample collected as scheduled.
* = Cage displaced, sample collected.
° = Sample missing, not collected.
X = Collected early in place of missing sample.

Results of GC/MS analyses of sediments from transect stations and mussels and SPMDs deployed at Smith Island are summarized in Table 6-12. In the SPMD analyses, interferences were encountered that in many cases prevented full quantitation of results for alkylated phenanthrenes.

Sediment Results

Summed PAH concentrations in sediment samples collected at stations along the two transects (Table 6-12) ranged over two orders of magnitude; all concentrations along the unoiled/lightly oiled south transect were less than 0.5 ppb, and all concentrations on the heavily oiled north transect were greater than 11 ppb. Differences between the sediment levels on the north and south sides were significant (Mann-Whitney U test, $p = 0.025$).

Mussel Results

Summed PAH results were compared for three groups of mussels (Barnes Cove transplant stock, reference Smith-south transplants, and Smith-north transplants). Results from the July recoveries were used because the July data set is complete across all stations and all stations remained in place along the transects. The nonparametric Mann-Whitney U test showed no significant difference between the PAH concentrations in tissues of the Barnes Cove stock mussels and the mussels deployed on the unoiled south side of Smith Island. Mussel tissue levels measured on the heavily oiled north side of the island, however, differed significantly from those on the south side ($p = 0.034$).

On the north side of the island, three mussel stations (N-2, N-4, and N-5) on the transect remained physically intact over the entire 52-day deployment. That is, three of the five cages remained at the designated stations and were not laterally displaced by wave and tidal action. This permitted an assessment of temporal changes in levels of accumulated PAHs between 14 and 52 days. In all three cases, summed levels of PAHs increased between the 14-day collection and the 52-day collection (Table 6-12). At station N-2, the PAH level increased from 1,600 ppb to 4,200 ppb; at N-4, from 1,800 ppb to 5,000 ppb; and at N-5, from 1,900 ppb to 5,500 ppb. The difference between the 14-day PAH levels and the 52-day levels was significant ($p = 0.05$) in the Mann-Whitney U test.

Table 6-12 Summed PAH results from Smith Island deployments. Results for sediments and mussels in ng/g (ppb) dry weight; for SPMDs, ng/SPMD.

Sample-date	Station									
			N-1	N-2	N-3	N-4	N-5	S-1	S-2	S-3
Sediments										
Sed-June			26	160	34	12	88	0.5	0.3	0.4
Mussels										
Xplant stock	11	27	—	—	—	—	—	—	—	—
Mussel-July			1,200	1,600	1,300	1,800	1,900	46	17	37
Mussel-Aug			3,100*	4,200	4,700	5,000	5,500	57*	—	n/a*
SPMDs										
SPMD blank	300	400	—	—	—	—	—	—	—	—
SPMD-July			1,000	—	1,100	1,200	2,300	380	640	—
SPMD-Aug			460*	1,900°	—	—	2,200	330*	—	280*

Key

* = Cage was displaced from original deployment location on transect.
° = SPMD originally scheduled for collection in August but collected in July in place of missing device.
n/a = Not analyzed.

Semipermeable Membrane Devices Results

Analytical results for PAH levels in the SPMDs were subjected to the same type of nonparametric tests used for the mussel results, and similar patterns were obtained. As was the case for the mussels, July results were used in these tests because collections were complete across both transects and because the stations along the transects were not physically disrupted. Application of the Mann-Whitney U test showed that there was no significant difference between summed PAH levels in laboratory blank SPMDs and the SPMDs deployed to the south side of Smith Island. Concentrations of PAHs in SPMDs deployed on the north side of the island differed significantly ($p = 0.025$) from those in SPMDs from the south side.

Only one SPMD station from either side of the island remained completely intact over the entire 52-day deployment. This station was N-5, along the northern transect. While other SPMDs were recovered on both sides of Smith Island in August, these had shifted in location between the 14- and 52-day collections and were not appropriate for direct comparisons. The single intact pair of SPMDs contained essentially the same levels of PAHs at both 14 and 52 days, 2,300 and 2,200 ppb, respectively.

Comparison of Sediment, Mussel, and Semipermeable Membrane Devices Results

The summed concentrations of PAHs in sediments, mussels, and SPMDs at stations on the north and south sides of Smith Island were compared using the Spearman rank correlation coefficient. Application of the test showed that results in all three matrices were significantly correlated in the levels of hydrocarbon uptake on the two sides of the island. Results from the Spearman rank procedure are summarized in Table 6-13.

Table 6-13. Results of Spearman rank correlation tests on summed hydrocarbon results from Smith Island.

Test	N	D^2	r_s	z	p
Sed vs. mussel	8	16	0.810	2.124	0.032
Sed. vs. SPMD	8	11.5	0.862	2.281	0.022
Mussel vs. SPMD	8	9.5	0.886	2.345	0.019

Key

N = Number of cases (five north stations and three south stations).
D^2 = Sum of squares of differences of ranks.
r_s = Spearman rho value.
z = Distribution transformation of r_s for significance testing.
p = Probability/significance.

Although the total concentrations of target PAHs in mussels and SPMDs showed similar patterns in short-term (14-day) uptake at the north and south transects (i.e., significantly higher concentrations at the oiled site relative to the unoiled/lightly oiled site; and no significant differences between the unoiled/lightly oiled site and blank or reference materials), the distribution of specific PAH compounds was somewhat different in mussels and SPMDs. A typical example of these differences from the 14-day collections at station N-5 on the north side of Smith Island is shown in Figure 6-4. The most readily apparent differences between the mussel and SPMD results are the compounds occurring in highest proportion. In the mussel sample, the alkylated phenanthrenes, and especially C-3 phenanthrene, are most prevalent. In the SPMD sample, the lighter PAHs, naphthalenes and fluorenes, dominate.

Cluster analysis was used to evaluate the complete set of 14-day mussel and SPMD results and to determine whether the differences in distribution of individual PAH compounds observed in Station N-5 results were consistent across the other samples and furthermore, whether the differences in PAH distribution were sufficiently great to result in distinct grouping of the samples by matrix and location.

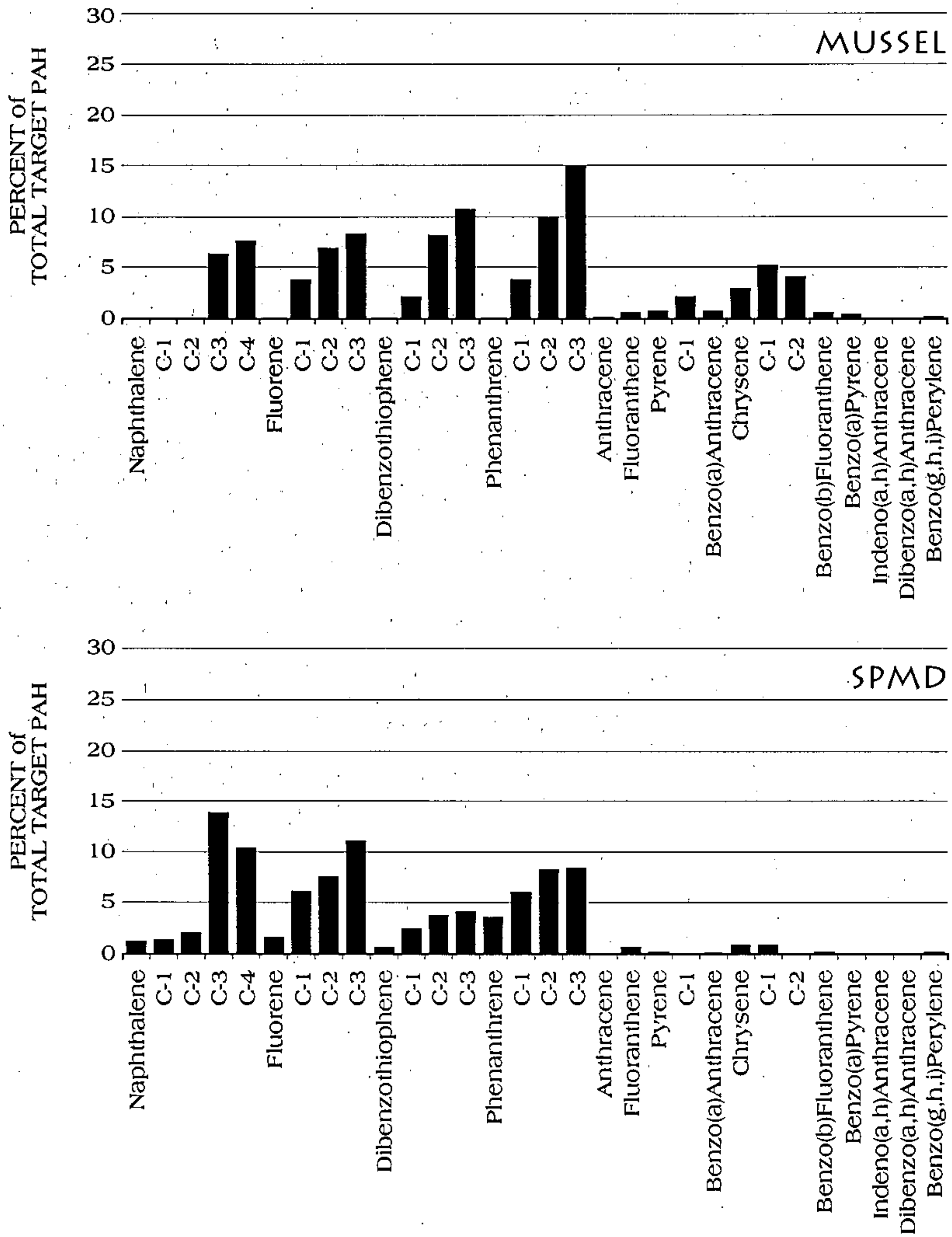

Figure 6-4. PAH profiles for transplanted mussel (top) and SPMD (bottom) samples collected at station N-5 on Smith Island in July 1992.

In the dendrogram resulting from the cluster analysis (Figure 6-5), the clusters correspond well to combinations of matrix and deployment location. Branch "A," for example, includes all ten SPMD results, including the method blanks. Branch "B" encompasses all of the mussels, including the transplant stock collected at Barnes Cove. Branch "C" represents all of the SPMDs deployed on the oiled north side of the island and one from the south side. The remaining SPMDs from the south side of Smith Island and the method blanks are grouped at the next level into this branch, at "D." Branch "E" contains all five of the mussels transplanted to the north-side transect. Finally, "F" clusters the south-side mussels and the Barnes Cove stock mussels.

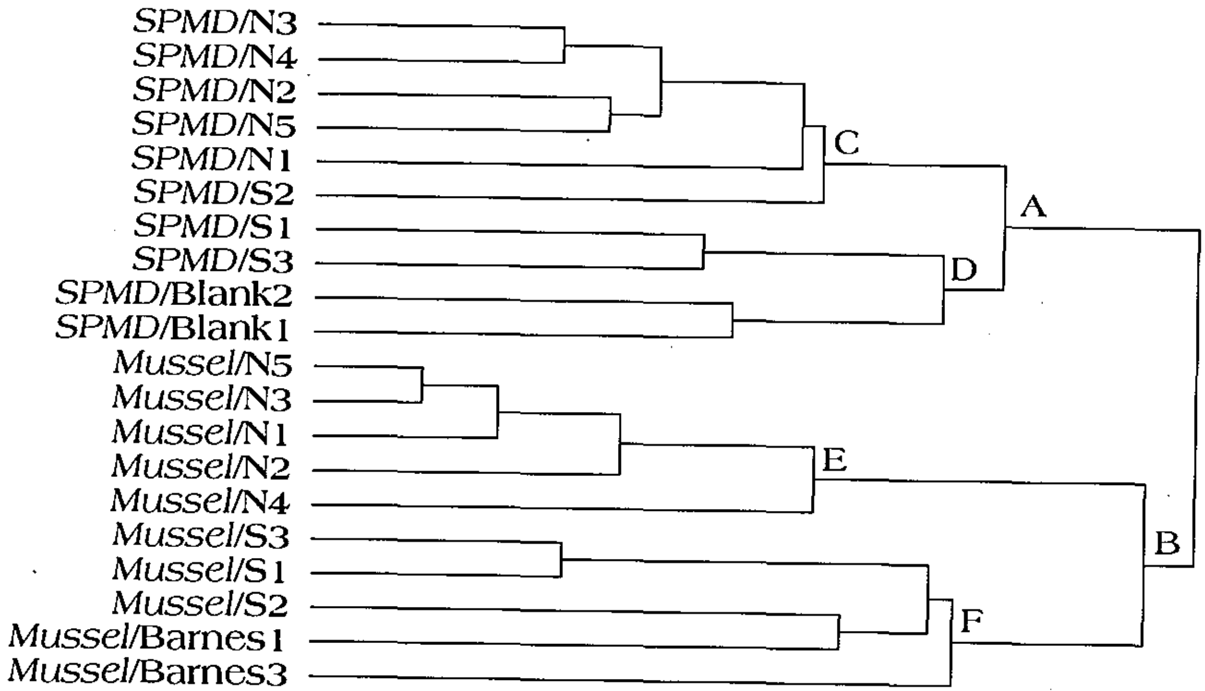

Figure 6-5. Tree diagram for cluster analysis of PAH distribution profiled for Smith Island mussel transplants and SPMDs collected in July 1992.

DISCUSSION

Because SPMDs, by design, passively sample the dissolved fraction of PAHs in the aquatic environment, their deployment in the environment in association with mussels can offer some insight into the mechanism of PAH exposure to the mussels. Specifically, comparison of results in SPMDs and mussels may elucidate the relative roles in determining accumulation in mussel body tissues of dissolved PAHs vs. PAHs associated with food or particulate material ingested during filter-feeding activities.

In this study comparison of results in mussels and SPMDs was complicated by the interferences encountered in the laboratory at GC elution times for the alkylated phenanthrenes. As these compounds are important constituents of the existing source on Smith Island and of the original *Exxon Valdez* crude oil, inability to quantitate them affected results of PAH profile comparisons. It is not clear whether the interferences were attributable to the deployment method (e.g., the use of plastic-coated-wire cages), or whether they are inherent for PAH compounds of this type that partition into SPMDs. In future deployments modified cleanup procedures may address these problems.

Regardless of their origin, the differences between the PAH uptake profiles in mussels and SPMDs encountered in this study are similar to those reported elsewhere for polychlorinated biphenyl uptake in paired deployments of clams and SPMDs (Prest et al., 1992). Prest et al. suggest that passive uptake processes (equilibrium partitioning) do not completely account for levels of PAHs found in mussels exposed to residual petroleum hydrocarbons. This in turn would indicate that: the route of exposure to SPMDs and mussels is different (i.e., PAHs in solution vs. PAHs adsorbed to particulate material or incorporated in food items); the mussels selectively metabolize some PAHs over others, perhaps eliminating lighter fractions such as naphthalenes or fluorenes more readily than other PAHs; or some combination of exposure and metabolism is responsible. The relative similarity of PAH profiles found in water/sheens/oiled sediments and in mussels, however, coupled with the relative dissimilarity of the exposure source profiles and profiles in SPMDs, suggests that mussels do not substantially alter target PAHs by metabolism.

The fact that levels of PAHs were significantly accumulated in SPMDs on the north side of Smith Island, relative to those on the south side, indicates that PAHs are available in the water flooding over the SPMDs and mussels. This would suggest that the route of exposure is associated either with truly dissolved PAHs in the water column or with PAHs in the sheens that were regularly observed to leach from the substratum on the north-side site. A more targeted study would be necessary to investigate exposure mechanisms in a definitive way.

The following summarize results for the study:

- ❐ Sediments collected from stations on the north (heavily oiled) side of Smith Island contained significantly higher concentrations of target PAHs than did sediments collected from stations on the south (unoiled/lightly oiled) side.

- ❐ Mussels and SPMDs deployed at the north-side transect accumulated PAHs to concentrations significantly greater than those deployed at the south-side transect.

- ❐ Total target PAH results in sediments, mussels, and SPMDs collected at the same stations were significantly correlated.

- ❐ Hydrocarbon uptake kinetics in mussels and SPMDs appear to be different. There was little difference in PAH levels in SPMDs collected after 14 and 52 days, but mussels showed significantly higher levels after 52 days.

- Although target PAH concentrations were similar in mussels and SPMDs after 14 days, the distribution of individual PAHs was different, particularly along the oiled transect.

Despite the fact that SPMDs showed clear differences in the nature of PAH uptake at oiled stations relative to that in mussels, they demonstrated their potential utility as monitoring tools. The devices effectively sequester lipophilic contaminants that occur at trace levels and, with further research into equilibrium partitioning coefficients, eventually could offer a means for estimating concentrations of contaminants in the environment. Furthermore, because of the selectivity in the mechanism of hydrocarbon uptake, SPMDs deployed in conjunction with traditional monitoring organisms can facilitate insights into ecological routes of exposure. The analytical difficulties encountered in this study with respect to interferences in quantitation of the alkylated phenanthrenes remain an area for more methodological research, however, as these compounds are important constituents of crude oil.

Although it is clear that PAHs remain biologically available to mussels on the oiled side of Smith Island, comparison of mussel PAH results from 1990 and those from the 1992 transplant experiment indicates that the degree of bioavailability of residual hydrocarbons has declined substantially (84,000 ppb in 1990 resident mussels versus approximately 6,000 ppb maximum in 1992 transplants). Nevertheless, the biological and ecological significance of the levels accumulated in intertidal organisms remains undetermined. The pathological consequences of a continued, relatively low level chronic exposure to the mussels are not known. It is also not known whether the tissue levels in the mussels pose any risk to predators that feed on them. While results discussed in Houghton et al. (1991) indicated no evidence of biomagnification of PAHs from mussels further up the food web into intertidal predators such as starfish and drills, recently some wildlife biologists (e.g., Patten, 1993) have asserted that reproductive failure in harlequin ducks in oiled regions of Prince William Sound may be attributable to the ducks' ingestion of contaminated mussels. At this time, however, this link remains speculative and is clearly a subject for further research before disruptive mussel removal projects are implemented.

CHAPTER 7

GENERAL DISCUSSION, SUMMARY, AND CONCLUSIONS

The general discussions, summary, and conclusions in this chapter are based on analyses conducted to date on samples collected in 1990, 1991, and 1992, as well as on newly released observations and data from 1989 (ERCE et al., 1990a, b).

OVERALL IMPLICATIONS OF THE FINDINGS

Multiple hypotheses relating to the effects of hydrocarbon contamination from the *Exxon Valdez* and to effects of subsequent shoreline treatments have been tested in the three years of this study (1990-92). Many of these null hypotheses have been rejected, and this rejection indicates significant differences in the condition of shorelines among our three categories of sites. For the majority of the variables tested, conditions do not differ significantly among Category 1 (unoiled) and Category 2 (oiled but not high-pressure hot-water treated) sites. For some variables, however, Category 3 sites (those that were high-pressure hot-water washed) remain different and are not fully recovered. In other cases, patterns apparent in the field or in the data were not statistically significant, but the data have been included and discussed to provide information on the direction of qualitative relationships among the categories.

Expectations for the qualitative relationships among the treatment categories vary with the nature of the variable. Opportunistic species of epibiota, for instance, would be expected to be more abundant at Category 3 or Category 2 sites in the early years following the spill. This greater abundance was evident in 1991 to a greater extent than in 1990, and high densities of opportunistic barnacles, littorines (*L. scutulata*), and algae (*Gloiopeltis* and several encrusting forms) were observed at Category 3 rocky sites. Of the infauna on mixed-soft beaches, high abundances of oligochaetes in Category 3 beaches in 1990 and of nematodes, oligochaetes, and some crustaceans and gastropods in Category 2 beaches might probably also represent opportunism. The long-lived community dominants such as mussels, drills, limpets, and rockweed, observed to have suffered heavy losses due to oiling and cleanup, would be expected to be less abundant at Category 2 and 3 sites immediately following the spill. This expectation was realized to a greater degree in 1990 than in 1991; by mid-summer 1991 recovery of many of these dominants had occurred on Category 2 sites to a far greater degree than on Category 3 sites. By 1992 recolonization by some of these dominants, most notably limpets and rockweed, had more than restored abundances at Category 3 sites, though others such as drills and foliose red algae remained depressed. The hardshelled clams represent a long-lived component of the infauna that has been particularly slow to recolonize Category 3 beaches. Reduced biological control or altered habitat conditions may cause some species to become more abundant for a time in the post-spill assemblage, and reduced grazer populations have allowed rockweed at the middle rocky stations to achieve a percent cover greater than that in the reference stations. This abundance, in turn, will influence recovery of other associated species.

The responses of organisms may be expected to vary between Category 3 and Category 2 sites. For example, recolonization by infauna could be expected to proceed differently on a beach with high residual oil in the sediments than on a beach where washing had removed some oil, along with fines and organic matter. In some cases, sufficient information was not available to develop hypotheses about the expected relationships. Thus, the information on the qualitative patterns must be interpreted separately for each taxon, site category, or variate examined. In cases where the existing data and knowledge do not permit explanation, continued monitoring may clarify the significance (if any) of these patterns.

The statistical testing performed on the 1990 data provided a strong basis to argue that conditions spanning a broad spectrum of biological properties reflected the influence of both hydrocarbon contamination and shoreline treatment, but that the effects of the treatment predominated (Houghton et al., 1991a). Similar testing completed on the 1991 and 1992 data has provided progressively fewer instances of significant differences between the site categories. These results—plus trends seen over time in key species abundance, directions of movement seen in principal components and multivariate analyses, and general observations during field cruises in the Sound—provide strong evidence that recovery is underway, even at the most severely affected sites. Although differences between unoiled (Category 1) and oiled but untreated (Category 2) stations were insignificant in 1991 and 1992 in most cases, several significant differences remain between biological conditions at either of those two station categories and conditions at high-pressure hot-water-washed (Category 3) stations. Thus, impacts evident in littoral assemblages in 1992 appear to be more the result of the high-pressure hot-water-wash treatments than of the oiling itself.

HYDROCARBONS

Sediment Chemistry

Sediment samples from lower mixed-soft stations only were analyzed for hydrocarbons in 1992, and patterns of residual PAHs in these samples were similar to those observed in previous years. Sediment concentrations of PAHs in 1992 were one to two orders of magnitude lower at unoiled (Category 1) sites than at oiled (Category 2) or oiled and hot-water-washed (Category 3) sites. The Block Island lower station had the highest sediment PAH level (0.78 ppm wet) measured in 1992; (although this value had declined from 3.8 ppm in 1991). Because of this high value from Block Island, lower mixed-soft stations at Category 2 sites had the highest mean PAH concentrations of any site category in both 1991 and 1992.

Hydrocarbon constituents in sediments analyzed in 1992, except at Block Island, were consistent with generally expected patterns of weathering of crude oil. In some cases, measurable contributions from potential diesel oil and/or combustion resources were found. Higher concentrations of naphthalenes and fluorenes in sediments at the lower Block Island station reflect isolation of crude oil trapped within the sediment column at that untreated station.

Several compounds occurred at sufficiently high concentrations in sediments at one station (Block Island lower) to raise concerns about sublethal effects of exposure. In the 1991 transplanting experiment there was a clear correlation between higher sediment hydrocarbon residuals and reduced survival and increased uptake of PAHs in littleneck clams. In 1992 the growth of clams from this transplant experiment was also seen to be negatively correlated with sediment hydrocarbon concentration.

Tissue Chemistry

Because of limitations in the analytical budget, mussel tissue hydrocarbons have been analyzed in all three years at only a single Category 1 site, where total target PAHs have declined since 1990; this decline possibly reflects level of activity in the nearby fishing camps. At most oiled sites mussel PAH concentrations dropped dramatically between 1990 and 1992. At exposed sites (Point Helen, Northeast Latouche, Sleepy Bay) declines were nearly an order of magnitude or greater. At more protected sites declines were less (e.g., 40 percent at Mussel Beach), and at Block Island, where sediments remain highly contaminated, mussel tissue PAH had declined little from 1990. Nonetheless, tissue concentrations in mussels from even the sites with the highest remaining sediment PAH levels in this study were comparable in magnitude to concentrations in mussels from near areas of human activity that were not directly affected by the spill (Seward and New Chenega).

Littleneck clam PAH accumulations measured in 1992 were generally well below those measured in 1991, except at Block Island. At the three Category 3 lower stations sampled, littleneck soft tissue PAHs declined by 50 percent or more and Snug Harbor concentrations also declined sharply (by 80 percent). Except at Sleepy Bay PAH levels in clams tended to be lower than those in mussels at the same site, possibly because they were collected from lower intertidal elevations with less exposure to residual oil.

INTERTIDAL ASSEMBLAGES

Epibiota

Analysis of two data sets from shoreline treatment effects studies conducted in 1989 for Exxon show that major components of the intertidal flora and fauna inhabiting Prince William Sound survived at least three to four months on heavily oiled beaches. Except for a few taxa, these organisms were generally present in abundances comparable to those at unoiled beaches in the sound. Based on these 1989 studies, the short-term effects of the use of high-pressure hot-water on intertidal flora and fauna of the sound were significant: all dominant taxa but one (barnacles) suffered from 60 to 100 percent mortality from treatments of less than three hours' duration.

The effects of 1989 shoreline treatments on intertidal biota remained evident and statistically significant at Category 3 sites monitored in 1990 (15 to 17 months following the spill); flora and fauna on Category 2 beaches more closely resembled those on Category 1 beaches. The majority of the community dominants was present on Category 2 beaches in abundances similar to those on Category 1 beaches, but reduced numbers of some species (e.g., limpets, rockweed, *Nucella*, and several infaunal taxa) indicate continued effects from oiling alone (see Figures 3-1, 4-2, 4-5, and 4-10).

In 1990 statistically significant differences (lower abundances) were seen in several of the dominant taxa of epibiota on rocky and mixed-soft (gravel/sand with some cobbles) beaches. Rockweed and limpets most commonly exhibited lower abundances on Category 3 beaches (cf. Category 1 beaches) at middle and upper intertidal levels. Other species showing significantly lower abundances at these beaches included littorine snails, hermit crabs, and mussels. At lower intertidal levels, effects of hot-water washing were not consistently evident in the epibiota in 1990. Filamentous green algae seem to have been more abundant at Category 2 and 3 stations than at controls, while several taxa of red algae showed the opposite pattern.

By 1991 substantial recovery had occurred at both Category 2 and Category 3 sites, although significant differences still remained (e.g., in limpet and rockweed abundances at middle rocky stations) between unoiled reference sites and Category 3 sites. Colonization of Category 3 sites by opportunistic species had been substantial, and community composition differed noticeably from that at Category 1 and 2 sites.

By 1992 the majority of the high-pressure hot-water-washed beaches appeared, at least superficially, to have recovered. This appearance was due to the proliferation of rockweed at middle rocky stations on Category 3 beaches, where cover exceeded that on Category 1 and 2 beaches. This increased cover of rockweed is likely the result of reduced numbers of grazers at Category 3 sites from 1989 through 1991. By 1992 limpet densities had also recovered at middle rocky stations, and more normal biological controls can be expected to become reestablished in future years. Abundances of some other important species remained altered at Category 3 middle rocky stations from the expected condition as represented by Category 1 middle stations. Hermit crabs, *Littorina sitkana*, *Balanus glandula*, *Semibalanus cariosus*, and some red algae were all more abundant at Category 1 sites; *L. scutulata*, *Gloiopeltis*, *S. balanoides*, and encrusting brown algae were all more abundant at Category 3 sites. This pattern suggests that an earlier stage of ecological succession was still extant at Category 3 middle rocky stations.

At the single lower elevation rocky station sampled in 1990 through 1992, examination of pretreatment (May 1989) data provided significant insight into the effects of treatment. Washing conducted at this station had no noticeable immediate effect on cover of rockweed (15.4 percent cover in May before treatment, 22.8 percent cover in June after treatment [ERCE et al., 1990a, b]); this apparent lack of effect suggested that temperatures used may have been lower or that wash durations were reduced (by shorter emersion time) from those experienced at the middle elevation station where rockweed was totally removed. Impacts of washing on a group of long-lived red algae were severe, however. Cover dropped from more than 70 percent to less than 20 percent immediately following the washing (ERCE et al., 1990b). During the next three years, cover of rockweed expanded to nearly 60 percent, and nonencrusting red algae have not exceeded 10 percent cover.

At least partial recovery of most variables characterizing intertidal epibiotal assemblages was apparent by mid-summer 1992. Few differences remained between unoiled rocky stations and stations that were oiled but not treated with high-pressure hot-water washes. Recovery at high-pressure hot-water-washed rocky stations, however, significantly lags behind that at oiled but untreated stations both in terms of reduced abundance of some taxa and increased abundance of others.

Infauna

Protected sand and gravel beaches were severely affected by hydraulic treatments, which altered beach morphology. Sands and finer gravels were flushed from upper intertidal elevations and often buried the lower beach in several centimeters of sediment. In 1992 differences remained in sediment grain size composition between untreated and treated (Category 2 and 3) beaches. Although not as evident as in 1991, coarser materials remained higher at Category 3 beaches. Category 3 beaches were also lower in organic content, an important energy resource for infauna.

Since many of the mixed-soft sites in this study were washed with landing craft vessels (LCVs) and beach parties using firehoses, it is probable that organisms on these beaches may have experienced somewhat lower maximum temperatures than those on beaches washed with Omni-barges or Maxi-barges (see Houghton et al., 1990a for a discussion of equipment commonly used). Lees et al. (1993) have considered LCV treatment to be "warm-water" rather than "hot-water" washes and note reduced impacts on epibiota from such treatments. For the purposes of this study, all three treatment types have been considered "hot water" in as much as all were capable of heating water to about 60°C. As discussed at length by Houghton et al. (1993), the initial impacts of hydraulic treatments on infauna, as well as their impacts on recovery of the infaunal community, are probably not heavily dependent on temperature. The majority of the initial loss is likely due to suspension or burial, with the physical buffering of the sediments themselves protecting much of the infauna from thermal impacts. Effects of hydraulic treatments on long-term recovery are likewise dependent on the changes in the physical structure of the beach and are thus unrelated to the temperature of the water used. Thus, we do not feel that the specific equipment used affects the infaunal results in this study. Impacts on infauna would likely have been similar even if cold- (ambient-) water flushes were used.

In 1992 as in 1991 and 1990, infauna appeared only moderately affected by the spill on Category 2 (oiled but untreated) beaches with few apparent differences between Category 1 (unoiled) and Category 2 stations. Abundance of infauna on Category 3 (oiled and hot-water-washed) beaches, however, remained low in comparison to both other category sites. Most major taxa (gastropods, bivalves, polychaetes, crustaceans) continued to have lower abundances on Category 3 beaches than on Category 1 and Category 2 beaches. Category 2 sites had substantial increases in all major taxa in 1992, including large increases in numbers of gastropods and crustaceans.

PCA of infaunal sites from 1990 to 1992 showed a clustering of two groups: an upper group of Category 3 sites and some of the more impoverished Category 2 sites and a lower group of the Category 1 sites and some Category 2 sites. The upper group included sites with coarser grain sediments and low species richness. The lower group formed around the sites with finer sediments and high species richness.

In 1992 the lower Category 3 stations continued to have the lowest overall density of hardshelled clams. The three Category 3 stations had virtually no littleneck clams

(*Protothaca staminea*). No butter clams (*Saxidomus giganteus*) were taken in cores at Category 3 sites in 1990, 1991, or 1992. In addition, only one *Saxidomus* was collected in 0.25-m^2 excavations from Category 3 sites.

Analysis of 1992 results and consideration of newly released 1989 data (ERCE et al., 1990a, b) support the assertion that the effects of shoreline treatments on infauna relate more to physical disturbance (burial, displacement, reductions in fines, and organic content) than to oiling. The 1992 data also are consistent with earlier projections that recovery of infauna on hydraulically washed beaches will take many years. The two hardshelled clam species, for example, likely will take more than 10 more years for full recovery (i.e., restoration of prespill age structure).

MOLLUSK STUDIES

Preliminary results of the tagging study in 1991 suggest that growth patterns for mollusks in Prince William Sound differed substantially from those reported in more temperate regions. All species examined appear to exhibit highly variable growth, in terms of when and how much they grow. This pattern of irregularity in growth for four of the dominant intertidal mollusks in the Sound strongly suggests that growth in many dominant invertebrates in Prince William Sound may be irregular or episodic. Proximity to northern range limits may provide a possible explanation for this pattern.

Analysis of age-frequency histograms for *Protothaca* suggested a partial mortality of all age classes at oiled Category 2 sites followed by highly successful recruitment in 1989 through 1992. At Category 3 sites 1989 mortality was more extensive, and subsequent recruitment has been less successful.

In 1992 mollusk growth studies were confined to *Protothaca staminea* collected from 0.25-m^2 excavations and from a transplant experiment. As in earlier years, significantly lower numbers of *Protothaca* were found at Category 3 sites, but they exhibited the best growth rates, perhaps because of reduced competition for food. Although replication was small, there were indications that littleneck clams transplanted to the Block Island lower station showed a negative growth response to increasing PAH concentration in the sediments. Best growth of transplanted clams occurred at the Category 3 Northwest Bay West Arm site, possibly because of reduced competition for food and/or higher water temperatures at that site.

TREATMENT RECOMMENDATIONS

The results of this study provide strong evidence that the impacts remaining in intertidal communities in 1992 were more the result of high-pressure hot-water treatments than of the oiling. Despite these results, a high degree of variability was obvious in late 1989 and in subsequent years in the impacts on heavily oiled and treated beaches of the Sound—for example, along the shorelines of Northwest Bay, Ingot Island, and Elrington Island, where many areas of apparently unaffected or minimally affected intertidal biota were interspersed with severely impacted areas. This variability and 1989 observations of the mode of applications of warm- and hot-water washes suggest that—with modifications to the operational guidelines and, more importantly, with strict control of field implementation—some effective cleanup of major oil concentrations could be accomplished in an environmentally acceptable manner.

It is of paramount importance that biologists and ecologists knowledgeable in the diverse resources of the region in question be involved in identifying real objectives of shoreline cleanup. Obviously, these objectives should seek to balance the net ecological benefit (weigh the costs to one resource against the benefits to another) with economic considerations related to fisheries, subsistence use, and recreation. Removal of all of the oil from a beach just because it is there is a poor cleanup objective from a biological perspective (e.g., if collateral damage is expected to be high and natural cleanup rapid), although it may be more acceptable from another perspective. While data from this study strongly indicate that the treatments applied in Prince William Sound were detrimental to intertidal life and delayed recovery of many areas, we recognize that there may be other overriding scientific or economic reasons for cleanup. The immediate need to wash Applegate Rocks and other areas where marine mammals were expected to pup in spring of 1989 is an example of a reasonable trade-off of intertidal productivity for the protection of critical habitat for other species.

Recent pressures to destroy unique mussel beds to remove oil trapped in the byssus mat (to protect harlequin ducks and black oystercatchers from alleged breeding failure) is a situation requiring far greater investigation before implementation. For example, bioavailability of the hydrocarbons, exposure potential for ducks to the hydrocarbons present at the beds in question, energetic cost to the population of loss of a food resource (is it better to have contaminated food or no food?), and linkage to breeding impacts should all be understood. Often the data to make these decisions are limited, and a course of action perceived to be good for one resource (e.g., washing an upper mixed-soft beach to protect habitat for eagle foraging) may be damaging to others (e.g., hardshelled clams on the lower beach; infauna prey for crabs or flatfish). As noted, observations and data from this study suggest that some beach cleanup can often be accomplished to meet one need (improving conditions for eagles) while protecting others (minimizing adverse impacts to lower intertidal zones).

Our specific recommendations, as they relate to rocky, boulder/cobble, and mixed-soft beaches like those in Prince William Sound, are as follows:

- ❐ Mechanical cleanup (pumps, shovels, scoops) of oil pooled in upper beaches, behind storm berms, and in tidepools often can remove large quantities of oil with minimal impact; however, observations from this study suggest that mechanical removal of oiled rockweed will not accelerate recovery.

- ❐ Low-pressure cool-water flushes may be effective and should be considered on rocky or boulder/cobble substrata early in a spill (when oil is relatively unweathered and mobile). As oil weathers (as in the case of the *Exxon Valdez*), increased temperatures and pressures become necessary to mobilize the oil for recovery, and the usefulness of such treatments should be balanced against the damage they will cause.

- On mixed-soft beaches, the pressure and flow rate of the wash should be controlled to minimize disturbance of the sediment column and beach geomorphology; on rocky and boulder/cobble beaches, temperature should be minimized (consistent with overall cleanup objectives) to protect epibiota.

- On mixed-soft beaches, high volume water flushes at any temperature have a high potential for impact to infauna (Chapter 4). Burial or dislodgment of infauna, changes in beach morphology and sediment structure, and loss of organic matter have the potential to degrade habitat for many years in sheltered environments. To limit impacts to the biologically productive lower beach (which in Prince William Sound was usually not directly impacted by oiling), cleaning should be conducted on low-angle beaches only when the waterline is above the mid-tide level (upper portion of the rockweed zone). Oil stranded below that level (e.g., in the middle and lower rockweed zone) in Prince William Sound was usually moist and without thick accumulations; in these areas natural processes appeared quite effective at oil removal, and direct washing seemed unnecessary.

- If high-angle rocky beaches are washed when the tide is low, oil washed from upper elevations may be carried through the lower zone to the water's edge with minimal impact to the biota of the lower shoreline. If washing lower elevations (in the rockweed zone) on these shores is necessary to ensure that the oil is fully flushed onto the water surface for pickup, only ambient water should be used. Long-term damage from hot-water washing of lower rocky intertidal areas is clearly evident at this study's Northwest Bay Rocky Islet site.

Presuming that a controlled release of oil for the purposes of spill research is unlikely to be permitted in the United States, an objective in the cleanup of the next moderate-to-large spill should be to include controlled experiments that can provide definitive information on the effectiveness and effects of cleanup methods applied. These experiments should include physical, chemical, and biological sampling of replicated pairs of cleaned and uncleaned sites stratified by habitat and cleanup method. Preferably, monitoring should be conducted before and after treatment and should be continued to document impacts of treatment on long-term bioavailability and impacts of hydrocarbons and recovery of assemblages affected by the oiling and treatment. It is only through a continual process of learning that we can begin to understand the effects of oil and cleanup activities in complex ecosystems, and it is only through that understanding that we can improve the effectiveness of spill response.

GLOSSARY

ANOVA	analysis of variance
API	American Petroleum Institute
BACI	Before, After, Control, Impact
cc	cubic centimeter
DCM	dichloromethane
DRA	detrended reciprocal averaging
EPA	U.S. Environmental Protection Agency
g	grams
GC	gas chromatograph
GC/MS	gas chromatography/mass spectrometry
GPS	global positioning system
ID	identification
IES	Institute for Environmental Studies (Louisiana State University)
KHP	potassium phthalate
km	kilometer
KOH	potassium hydroxide
LCV	landing craft vessel
PAH	polycyclic aromatic hydrocarbon
m	meter
ml	milliliter
MLLW	mean lower low water
mm	millimeter
MMS	Minerals Management Service
MS	mass spectrometer
ng	nanogram
NMDS	nonmetric multidimensional scaling
NOAA	National Oceanic and Atmospheric Administration
PCA	principal components analysis
PCORD	principal coordinates analysis
ppb	parts per billion
ppm	parts per million
ppt	parts per thousand
QA/QC	quality assurance/quality control

SD	standard deviation
SE	standard error
SPMD	semipermeable membrane devices
TOC	total organic carbon
T/V	tanker vessel
USCG	U.S. Coast Guard
μl	microliter

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